Rotation in the Orion Nebula Cluster

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ABSTRACT

Eighteen small (4 arc-min square) fields within the Orion Nebula Cluster (ONC) have been photometrically monitored for one or more observing seasons between 1990 and 1999 with a CCD attached to the 0.6 m telescope at Van Vleck Observatory on the campus of Wesleyan University. Data were obtained exclusively in the Cousins I band on between 25 and 40 nights per season. Results from the first three years of operation of this program were summarized and analyzed by Choi & Herbst (1996). Here we provide an update based on six additional years of observation and the extensive optical and infrared study of the cluster by Hillenbrand (1997) and Hillenbrand et al. (1998). Rotation periods with false alarm probabilities (FAP) $< 1\%$ are now available for 134 members of the ONC. Of these, 67 were detected at multiple epochs with identical periods by us and an additional 15 were confirmed by Stassun et al. (1999) in their study of Ori OBIc/d. Therefore, we have a sample of 82 stars with virtually certain rotation periods and another 52 with highly probable periods, all of which are cluster members. The bimodal period distribution for the ONC reported by CH is confirmed but we also find a clear dependence of rotation period on mass. This phenomenon can be understood as an effect of deuterium burning, which temporarily slows the contraction and, therefore, spin-up of stars with $M \leq 0.25\ M_\odot$ and ages ~ 1 My. Stars with $M < 0.25\ M_\odot$ have not had time to bridge the gap in the period distribution at around 4 days. Excess H-K and I-K emission, as well as CaII infrared triplet equivalent widths (Hillenbrand et al. 1998), show weak but significant correlations with rotation period among stars with $M > 0.25\ M_\odot$. Our results provide new observational support for the importance of disks in the early rotational evolution of low mass stars.

Key words: stars: pre-main sequence - stars: rotation - clusters: individual: Orion Nebula Cluster

1. Introduction

It has long been recognized that stars must lose an enormous amount of angular momentum as they make the transition from a protostellar state to the main sequence. When and how they do this is still uncertain (cf. Bodenheimer 1995). The youngest visible stars, T Tauri stars, are typically rotating at only about one-tenth of their critical velocity, as first shown by Vogel & Kuhi (1981) and later confirmed by Bouvier et al. (1986) and Hartmann et al. (1986). Rotational studies of the youngest nearby cluster - the Orion Nebula Cluster (ONC) - indicate that about 2/3 of the low mass members are slow rotators but the rest spin at higher rates, even approaching critical velocity in the most extreme cases (Attridge & Herbst, 1991, hereinafter AH; Choi & Herbst 1996, hereinafter CH; Stassun et al. 1999, hereinafter SMMV). This wide range in spin rate and bimodal character of the frequency distribution persists in clusters as old as the Pleiades ($\sim$ 120 My; Stauffer et al. 1994).

Many attempts have been made to model the rotational evolution of low mass stars and account for the frequency distribution of rotation periods in clusters of various ages (e.g. the recent work of Bouvier 1997, Krishnamurthi et al. 1997, and Barnes et al. 1999). Surface angular momentum losses through magnetized winds and by redistribution in the stellar interior are important processes which may act on timescales of around 10^7 - 10^8 yrs. They can account for the evolution of rotation from the T Tauri phase on. However, they cannot explain the generally slow rotation and the existence of a wide range of angular velocities in a cluster as young as the ONC. Much more efficient angular momentum regulation mechanisms are needed which operate on a timescale of $\sim$1 Myr or less.

The most commonly invoked angular momentum regulation mechanism during the pre-main sequence phase is sometimes called "disk-locking" and based on an application by Königl (1991) of the Ghosh and Lamb (1979) theory of magnetic interaction between a rotating central star and an accretion disk. Somewhat similar proposals were made by Cameron & Campbell (1993) and Shu et al. (1994). In all cases, it is possible to account for the typical rotation period of a T Tauri star or slow rotator in the ONC ($\sim$8 days) with reasonable parameters for magnetic field strengths, accretion rates, etc. Edwards et al. (1993) discussed evidence of a link between rotation rates and disk indicators such as IR excess which they interpreted as support for this disk-interaction model of angular momentum evolution. These successes have led to a widespread adoption of some form of disk-locking in most models of rotational evolution (cf. Li & Cameron 1993; Cameron, Campbell & Quaintrell 1995; Bouvier 1997; Krishnamurthi et al. 1997; Barnes et al. 1999).

The ONC is a critical cluster for studying early angular momentum evolution since it provides the largest sample of extremely young stars in the solar vicinity. It has also been studied

extensively by a variety of techniques and masses, ages and infrared excesses attributable to disk emission are available for about a thousand cluster members (Hillenbrand, 1997; Hillenbrand et al. 1998). Rotation periods for some members of the Trapezium Cluster, which is at the heart of the ONC, were discovered by Mandel & Herbst (1991). This was followed by a more extensive study of the ONC by AH who found that the period distribution in the cluster was bimodal. Further work, by CH, confirmed that there are two peaks in the period distribution (near 2 days and 8 days) with a gap between them. CH interpreted this in terms of the disk-interaction models. The long period peak is composed of stars which are either currently interacting with their disks or have just recently been released from them. The gap is caused by the rapid spin-up expected for extremely young, contracting stars which are evolving under conditions of angular momentum conservation. The peak at 2 days is a binning phenomenon - there are relatively few bins available for rapid rotators when period, rather than (say) angular velocity is used as the independent variable. Recently, SMMV reported rotation periods for 254 stars in Ori OB Ic/Id, including 104 stars which are proper motion members of the ONC. They questioned the statistical significance of the bimodal distribution and the mechanism of disk-locking.

In this paper we summarize results on rotation in the ONC based on nine years of monitoring at Van Vleck Observatory. The observations are outlined in Section II, followed by a discussion of our period detection techniques and results. With firmly established rotation periods for 134 members of the ONC we are in a position to analyze, in Section III, how rotation depends on mass, age, disk properties, etc. This leads to a discussion, in Section IV, of what our data imply for the rotational evolution of young, low mass stars. In contrast to the results presented by SMMV, we find new support for a disk-regulation model of angular momentum evolution and explain how and why our results differ from theirs. Throughout the paper we rely on the same pre-main sequence models adopted by Hillenbrand (1997) to derive masses and ages, namely those of D'Antona and Mazzitelli (1994; DM94).

2. Observations, Reductions and Rotation Periods

Data were obtained over 8 observing seasons from 1990/91 through 1998/99 with a CCD attached to the 0.6 m telescope of the Van Vleck Observatory on the campus of Wesleyan University in Middletown, CT. For the first 7 years, the camera employed a 512x512 chip; last year it was replaced with a 1024x1024 chip. The descriptions and statistics that follow refer to the first 7 years; only the field size and locations have changed with the advent of the larger chip. Earlier papers in this series have discussed the results in 1990/91 (Mandel & Herbst 1991), 1991/92 (AH) and 1992/93 (CH). A paper on the Trapezium Cluster was also published by Eaton, Herbst & Hillenbrand (1995). The observing and reduction procedures are unchanged from what was described by CH. Briefly, we obtain five consecutive one-minute exposures in I from one to three times each clear night for each of the fields in our program. The locations of the fields are shown in Figure 1, which is centered on the Trapezium stars. Plus signs (+) mark the location of the

1053 stars from Jones and Walker's (1988) study that are within the area surveyed by Hillenbrand (1997). Filled circles indicate stars with rotation periods discovered by us. At the distance of the ONC (470 pc), 0.1deg $\sim$ 0.8 pc, so the area shown is roughly the extent of the dynamical ONC cluster modeled by Hillenbrand and Hartmann (1998), $\sim$ 2 pc. The Trapezium cluster is the inner $\sim$ 0.2 pc, or about the size of the small central square in Figure 1. According to Hillenbrand and Hartmann (1998) the Trapezium cluster should be regarded as the core of the ONC rather than as a separate entity. However, it does appear to be the youngest portion of the cluster and is certainly the densest. Figure 2 gives the naming scheme for our fields and Table 1 gives the Jones and Walker (1988; JW) number for the central star of each field. The table also indicates the years during which a particular field was monitored, the number of stars for which we obtained photometry (N), and the number of JW stars within the field. Although we monitored 69 stars in the fields which were too faint to be in the JW catalog, only one of these was found to be periodic, probably because of increased photometric errors (see below). Our most intensive monitoring has been directed at the Trapezium cluster, which has been monitored every year.

Aperture photometry is performed on all stars in the images using standard IRAF tasks. Comparison stars are identified by an iterative process which results in the selection of 4 or more non-variable or slightly variable stars, whose average magnitude (not flux) defines the comparison value. Typical errors are 0.015 mag for stars brighter than about I = 14. We can only establish variability, therefore, for stars with amplitudes exceeding about 0.05 mag. Although we find many irregular variables we defer discussion of them to a later paper. Here we discuss only those stars whose variations are strictly periodic in at least one observing season.

The periodogram technique discussed by Scargle (1982), as implemented by Horne & Baliunas (1986), was used to search for periodic variables. All stars were examined independently in each season, and a combined periodogram was formed by multiplying those obtained in individual seasons. The combining procedure did not reveal any stars which we would have missed by looking only at individual seasons, but it did yield some potentially interesting information about a few stars which is described in the footnotes to Table 2. The false alarm probability (FAP) defined by Horne & Baliunas (1986) was used to identify stars with likely periodic variations. A threshold value of 1% was employed when only a single observation per night was available or when multiple observations per night were averaged. As discussed by Herbst & Wittenmyer (1996), the standard FAP prescription assumes uncorrelated data and that may not be a valid assumption when there are multiple observations per night. In fact, one will obtain highly misleading FAP estimates if the standard prescription is used under these conditions, which will lead to the false identification of rotation periods for stars whose variations are probably random. To avoid this problem, we use a Monte Carlo method (cf. Herbst & Wittenmyer, 1996) to get a more realistic estimate of the FAP. In any event, our final test is to examine the light curves for all stars with possibly real periods. If the light curve is not convincing, we reject the star as a real periodic variable despite what the FAP statistic may indicate. In practice, only a few stars are rejected because of their light curves and we find the Horne & Baliunas prescription, as well as our Monte Carlo method, to be fairly

reliable.

Even when a reliable statistic is used, however, it must be expected that about 1% of the stars searched for periodicity will, in fact, turn out to be false alarms. The advantage of repeating this work in multiple seasons is that we can gradually isolate a sub-sample which is free of false alarms by finding stars which are periodic in more than one season. The chance of a false alarm occurring twice for the same star (with the same period!) in different seasons is, of course, negligible. Table 2 summarizes our results after 8 seasons of observation. The stars are divided into two groups in what follows - those found to be periodic at more than one epoch (including those with matching periods reported by SMMV) and those found to be periodic in only a single season. The first group can be regarded as consisting of stars whose periods are established with certainty while the second group could still contain false alarms. It is gratifying to note that in virtually all cases, when a star was found to be periodic in two different years, the periods were identical to within the errors. The only exceptions were a couple of cases in which an harmonic or an alias of the period was found (see notes to Table 2). In all, there are now 82 stars with firmly established periods (multiple season detections) and an additional 52 with likely periods (single season detections).

Light curves for some of these stars have already been displayed by CH or AH. We show light curves for the rest in Figure 3. In all cases, the periods, amplitudes and shapes of the light curves indicate that these are spotted variables whose periodicity is caused by their rotation. We identify the period as the rotation period of the star. A completely independent check of our results is now provided by the work of SMMV. We have 47 stars in Table 2 which are in common with them. In 44 cases the periods reported by SMMV agree with ours to within the errors of the determination. This is a gratifying comparison for both studies and reinforces our confidence in the methodology and basic result that we are, indeed, measuring rotation periods for these stars. Since the SMMV time span is rather short (at most 17 days and, in many cases, only 11 days) their periods are more uncertain than ours, so we do not include their values in our averages. We do, however, consult their data when the stars are divided into single and multi-epoch detections.

The cases in which significantly different periods are reported are as follows (with our period and the SMMV period given, respectively): JW 379 (5.62, 11.3), JW 843 (5.38, 0.84) and JW 984 (8.44, 1.13). JW 379 is a case in which our period is one-half of that reported by SMMV. They suggest that this may be an example of period doubling caused by spots on opposite hemispheres of the star. Alternatively, the star may have changed its spot characteristics during the single cycle over which they observed it. Their light curve clearly shows two minima. Here we adopt the longer period, recognizing that additional photometry is needed to be certain about which period is the proper estimate of the star's rotation period. We, therefore, do not regard the star as a multi-epoch detection in what follows. The two periods (P) found for both JW 843 and 984 are examples of "alias pairs" discussed by CH. They are related by $1 \pm 1/P$, i.e. the beat frequency with a one day sampling interval. Since SMMV have better time resolution and have data obtained at widely separated longitudes they should be less sensitive to aliasing problems. However, the light curve shown by SMMV for the 1.13 day period of JW 984 is not convincing,

especially given the short time interval over which they observed the star. We, therefore, have adopted the longer period for this star but, to emphasize the uncertainty have not included it among the multi-epoch period detection sample. Obviously, further data is necessary to resolve its period. The same is true of JW 843, which was only a single epoch determination to begin with and, in light of the uncertainty over its true period, we continue to regard as such.

3. Results

3.1. The Periodic Sample

Of the 134 periods discovered as a result of the VVO monitoring program, 133 of them have JW proper motions, and only one star (JW 794) has a membership probability less than 50%. In most cases, the proper motions indicate membership in the ONC for our periodic stars at the 99% confidence level. Figure 4 shows the color-magnitude diagram for all of the JW stars monitored in our fields, with the periodic stars marked by solid circles and the rest by plus signs. It is apparent from this diagram that our limit for detecting periodic stars is about I $\sim$ 16, although we monitored fainter objects. It is also apparent that most of our periodic stars are brighter than I $\sim$ 14, and below that we presumably have an increasingly difficult time detecting periods. This is almost certainly due to the fact that the errors of the photometry, especially for stars embedded in nebulosity, become larger at those magnitudes making it more difficult to find periods, especially for stars with smaller amplitudes. We note that, in addition to the 665 JW stars in our fields, we monitored 69 stars which were not included in the JW survey because of faintness, but are included in Hillenbrand's (1997) study. Only one of those stars, number 3128, was found to be periodic. Essentially then, our period monitoring program can be considered limited to the JW sample and somewhat incomplete below I $\sim$ 14 mag. For stars brighter than I = 14 mag, we detected periods in 33% of those monitored. Except for the OB stars, none of the objects in our fields are saturated, so there is no incompleteness on the bright end. There is an apparent paucity of periodic stars with I mag brighter than 10, which may be real. Altogether, we have monitored about 63% of the JW stars in the ONC; this number is fairly independent of magnitude range. It is clear from Figure 1 that our concentration is towards the center of the cluster, where the fraction of monitored stars which are cluster members is presumably highest.

Every periodic star in our JW sample has had its mass derived by Hillenbrand (1997) and, in Figure 5, we show their distribution (bottom panel) compared to the mass distribution of all JW stars within the monitored fields (top panel). It is clear that uncertainties in the photometry for fainter stars limit our ability to find periods for the lowest mass stars (M $<$ 0.25 $M_\odot$). The mass distribution of periodic stars peaks between 0.25 and 0.5 $M_\odot$ whereas for the cluster as a whole, the mass distribution continues to rise well below our limit for detecting periods. In the periphery of the ONC it should be possible to push the period detections to fainter, lower mass stars by using larger telescopes or longer exposure times. However, in the center of the cluster this may

prove difficult (at least from the ground) because of the nebular background brightness.

3.2. The Bimodal Period Distribution and its Dependence on Mass

The frequency distribution of rotation periods in the ONC was discovered to be bimodal by AH and the result was confirmed by CH, but recently questioned by SMMV. In Figure 6 we show the period distribution based on the current sample, which is 75% larger than that analyzed by CH. The bimodal nature described in the earlier work remains clearly visible, with peaks near 2 days and 8 days and a gap at 4 days. The small tail of more slowly rotating stars out to at least 20 days and possibly 34 days is also apparent. We test the statistical significance of the gap below, but first discuss the dependence of rotation on mass.

Figure 7 shows the distribution of mass with rotation period for our sample. Multi-epoch detections are shown as solid circles and single-epoch detections as crosses. An enlarged view of the boxed area in the top panel is shown in the bottom panel. It is immediately apparent from this plot that the lower mass stars ($M < 0.25$ $M_{\odot}$) have a more uniform distribution of periods than do those of higher mass. In particular, the gap in the period distribution around 4 days, which is quite obvious for stars in the range $0.25 < M < 1.0$, is closed for stars less massive than 0.25 $M_{\odot}$. This may be seen more clearly in Figure 8, where we show histograms of the period distribution for the higher and lower mass stars respectively. Two principle differences may be noted. First, the gap at 4 days is obviously quite strong in the higher mass distribution but absent among the lower mass stars. A more subtle, but nonetheless apparent difference in the distributions is the relative lack of stars with very short periods among the lower mass stars. As is shown below, both of these features can be understood in terms of mass-dependent rotational evolution.

Although the period distributions shown by CH and in Figures 6 and 8 of this paper, are obviously bimodal, the statistical significance of the gap at 4 days was recently questioned by SMMV. They claim that the CH distribution between 1 and 10 days is not significantly different from a uniform distribution. The basis for this is a Kolmogorov-Smirinov (K-S) test which shows essentially no difference between a "model" uniform distribution and the actual distribution at about the one sigma level. The problem with this is that the K-S test is not sensitive to gaps in the data, as SMMV themselves note. Obviously, therefore, the K-S test, and other cumulative distribution analyses like it, are inappropriate for evaluating the reality of gaps. They will give misleading results if applied and believed.

Fortunately, a simple, appropriate statistical test for bimodality does exist - the Double-Root Residual (DRR) method discussed in an astronomical context by Gebhardt & Beers (1991) and Ashman, Bird & Zepf (1994). This involves calculation of a quantity, the DRR, defined as:

$$DRR = \sqrt{2 + 4N} - \sqrt{1 + 4A}$$

for all non-zero values of N, where N is the number of objects in a particular bin and A is the average number of objects in a bin. The advantage of this statistic is that it indicates exactly where the data and the model differ from each other and gives directly the significance level of the difference. That is, a value of DRR=2, for example, corresponds to a discrepancy between the data and the model at the 2σ (95%) confidence level. Technically, the DRR test does not test for bimodality *per se* but for the significance level of features such as peaks and a gap. If a single significant gap is found between two relative peaks, however, the logical inference is that the distribution is bimodal.

In Figure 9 we show three truncated period distributions which are tested for significant gaps using the DRR method. We chose the interval 1 - 9 days as a convenient compromise between the 1-10 and 1-8 day uniform distribution "models" which SMMV test. The top panel shows the CH distribution as modified by SMMV, which they claim is not significantly different from a uniform distribution based on a K-S test. The DRR test, in the top right panel, indicates otherwise. The gap around 4 days is significant at about the 3σ (99%) level, by itself, and when the positive peaks on either side are considered, the statistical significance of the gap is enhanced. The middle and lower histograms are for the full sample of periods discussed in this paper and for the sample with M $>$ 0.25M$\odot$. In all cases, the DRR test indicates that the gaps are real and that the distributions, therefore, may be regarded as bimodal, both qualitatively and quantitatively.

3.3. Correlations of Rotation Period with Position in the Cluster, IR excess and CaII emission

We have searched for correlations between the rotation period and other measurable characteristics of the stars, and have found four. In all cases, the correlations are relatively weak, but Spearman Rank-Order Correlation Tests (e.g. Press et al. 1986) indicate they are significant at the $\sim$ 99% confidence level or better. The data, which are taken from Hillenbrand (1997, 1999) and Hillenbrand et al. (1998) are listed in Table 3, the four correlations are displayed in Figures 10 to 13, and results of the statistical tests are given in Table 4. These include the Spearman correlation coefficient, the probability that this correlation would arise by chance in an uncorrelated data set, the slope of a linear least squares fit to the data and the 1σ error of the slope. Since there is no reason to expect a linear relation between rotation period and any of the other quantities, the non-parametric Spearman statistic should be the more reliable indicator of a correlation. It also has the virtue of depending only on the rank order of the data, not on actual values, so it is a more robust test than the least squares fits in the sense that one or two extreme values (such as the unconfirmed period at 34 days) will have little effect on the results. It may be seen from Table 4 that the Spearman tests indicate uniformly higher significance levels than do the linear least squares fits, but even these indicate significant slopes for all the correlations except H-K at the $\sim$ 95% confidence level or better. Since rotation periods are derived in a manner which is *totally independent* of the other parameters, and since there are many possible ways in

which correlations such as these could be destroyed, but none (which we can think of) by which they could be falsely created (i.e. other than by a real physical process), we find them impressive in spite of their relative weakness. Added to this is the fact that all four correlations have simple physical interpretations which may account both for their existence and their sense.

Figure 10 shows the correlation that exists between rotation period and location within the ONC, measured by the projected radius (in arc-minutes) from the cluster center (Θ^1 Ori; Hillenbrand 1997). As Table 4 indicates, the correlation is quite significant, even though the correlation coefficient is fairly small. This remains true even if we exclude the star with a rotation period of 34 days. It is also apparent that the correlation exists among the sample of multi-epoch stars by themselves. A similar correlation was noted by CH and by Eaton, Herbst & Hillenbrand (1995), who showed that the period distribution in the Trapezium cluster (the central $\sim$ 4 arc-minutes of the ONC) included more stars with longer periods than was the case in the remainder of the ONC. While the Trapezium cluster has sometimes been regarded as a separate entity (e.g. Herbig and Terndrup, 1986), Hillenbrand and Hartmann (1998) consider it to be merely the center of the ONC. However, Hillenbrand (1997, 1998) has shown that there is an age gradient within the ONC in the sense that the center is younger, and that the fraction of stars with disks, as indicated by IR excess emission, is higher towards the center. The correlation presented here, therefore, associates longer rotation periods with the portion of the ONC which is both younger and contains more stars with disks. Since contracting stars will spin faster as they age, in the absence of an angular momentum loss mechanism, the correlation with position in the cluster may simply reflect the extreme youthfulness of the center of the ONC relative to its outer parts. Alternatively (or, in addition) if the disk-interaction mechanism is operating to drain angular momentum, then stars with disks may, in general, rotate more slowly than those without disks. Either, or both, physical effects could account for the existence and sense of the observed correlation.

Figures 11 and 12 show two measures of IR excess and their correlation with rotation period. The I-K excess is taken from Hillenbrand et al. (1998) and has the advantages of being available for more stars and involving a longer color baseline, which should make it easier to identify significant disk emission. However, the ubiquitous variability of the stars in I and the non-simultaneity of the measures at different wavelengths increases the scatter in the data. Nonetheless, a significant correlation between rotation period and I-K excess does exist among stars more massive than 0.25 $M_\odot$ in the sense that stars with larger IR excesses tend to have longer rotation periods. Again, removing one or two extreme stars has little effect on the Spearman test results (although it can change the least squares slopes more dramatically). The same results are obtained when the H-K excess (Table 3) is examined. In this case, the scatter is smaller, presumably because of the lower variability of the stars in H and the near simultaneity of the measurements at different wavelengths. On the other hand, there are fewer stars for which these data are available and the color baseline is smaller. The net result is that a correlation exists with about the same (Spearman) coefficient and at about the same significance level as for I-K, although the least

squares solutions do not indicate a significant slope. Taken together, these figures indicate a reasonable likelihood that rotation period is, in fact, correlated with the presence of disk emission. This supports the results of Edwards et al. (1993) who presented a similar correlation among a group of stars which partially overlaps with our sample, but is mostly independent of it. The physical interpretation proposed by Edwards et al. (1993) was that disks (can) act to slow the rotation of stars through magnetic interaction (Königl 1991; Ostriker & Shu 1995); hence, stars with disks may either be still "locked" to them or just recently released and will, in either case, tend to be slower rotators than stars whose disks were dissipated at earlier times.

Finally, in Figure 13, we show one additional correlation which exists and is important in spite of its weakness. This is between rotation period and equivalent width (EW) of the CaII infrared triplet (negative values indicate emission) as measured by Hillenbrand et al. (1998). This is an entirely independent measure of disk "strength", presumably reflecting the current accretion rate. Again, the sense of the correlation among the stars more massive than 0.25 $M_{\odot}$ is consistent with what one would naively expect if the disk-interaction scenario of Edwards et al. (1993) were valid. Stars with rotation periods shortward of the gap in Figure 13 almost all have CaII in absorption, indicating weak or non-existent accretion. Stars with rotation periods longward of the gap may also be in absorption, but have an average EW (CaII)= -0.03 ± 0.38, which is significantly less than the corresponding value (1.49 ± 0.32) for stars shortward of the gap. As was the case for IR excess emission, it is difficult to conceive of observational circumstances or selection effects which could conspire to create a correlation such as this in our data set, by chance, while it is easy to imagine how the correlation might be destroyed, even if the disk-locking mechanism were operative. In addition to random errors and false alarms among the periods, there could be complexities in the disk-interaction process which might obviate naive expectations about even the sense of the correlations. For example, higher accretion rates are expected to cause the radius of co-rotation to shrink and the rotation period, therefore to decrease in disk-locking models. This would produce a trend in the data which is counter to that expected in a simple "locked" or "not locked" scenario. The existence and sense of the observed correlations are, therefore, more interesting to us than the relatively small values of the correlation coefficients. We turn now to a discussion of the results in terms of models of rotational evolution.

4. Discussion

4.1. Understanding the Dependence of Rotation on Mass

Perhaps the most interesting new result described above is the dependence of rotation period on mass, illustrated in Figures 7 and 8. Can we understand why the gap in the period distribution disappears for stars less massive than about 0.25 $M_{\odot}$ and why there are substantially fewer very rapid rotators among these lower mass stars? To address this issue we consider the expected behavior of rotation period with mass and age under conditions of angular momentum

conservation, based on the models of DM94. For definiteness we adopt an initial rotation period of 10 days for a star at an age of 0.07 My. Changing the initial period by some scale factor is equivalent to adjusting the entire period evolution by the same factor - the shapes of the curves remain the same. The evolution of period with age for four different masses is shown in Figure 14. We have assumed homologous contraction for these entirely convective stars, so the period (P) depends only on the radius (R) as $P \propto R^2$. The rapid decline in period during the first few hundred thousand years reflects the rapid contraction of these stars during the earliest phases of PMS evolution.

At first, there is no difference between the evolution of higher and lower mass stars. However, by an age of $\sim$ 1 Myr (typical of the ONC) the lower mass stars are rotating with much longer periods than the higher mass stars. The physical basis for this is the so-called deuterium burning "main sequence". Low mass PMS stars are expected to survive their protostellar evolution with most or all of their initial deuterium abundance intact (Palla and Stahler 1999). When the interior temperatures get high enough, deuterium burning is initiated and the contraction towards the main sequence is temporarily slowed. Since P is quite sensitive to R, this evolutionary effect becomes quite obvious in the rotation period tracks of the lower mass stars. Stars more massive than ~ 0.3 $M_\odot$ go through deuterium burning too rapidly and at too early a time for it to be important to their observable period evolution. This may even happen during the protostellar stage (Palla & Stahler 1999) rather than the PMS stage. After $\sim$ 2 Myr the difference between the masses has largely been erased.

We find it intriguing that this simple, heuristic model can account for the observed difference in period distributions between the higher and lower mass stars in the ONC. Stars with $M < 0.25$ $M_\odot$ which have evolved without disk locking should have periods of around 4 days, whereas more massive stars should have periods of around 2 days. In other words, the lower mass stars are expected to lie within the "gap" defined by the period distribution of the higher mass stars - precisely as we observe. If there is an age range in the cluster, as expected, the oldest low mass stars might have had time to spin up to periods near two days, but the most rapidly rotating lower mass stars will have significantly longer periods than the higher mass stars until ages of about 2-3 Myr. We can, therefore, also understand on the basis of this scenario the relative lack of very short periods among the low mass stars, assuming the oldest of them is about 2-3 Myr. Note that starting radii for our calculations are about equal to the birthline radii for stars of the same mass (e.g. Stahler 1999) so the rapid period evolution expected during the early PMS phase is not obviated by the consideration of a finite starting time or radius corresponding to the protostellar stage.

4.2. The Disk Locking Hypothesis

AH first suggested and CH established in more quantitative fashion that the disk locking hypothesis of Königl (1991) and/or Ostriker and Shu (1995) provided a theoretical framework

within which one could understand the rotation period distribution in the ONC and, in particular, its bimodal nature. Longer period stars are interpreted as being still locked or only recently released from their disks. Shorter period stars are interpreted as having been released early in their PMS evolution to spin up in the fashion depicted in Figure 14. The end of the disk-locking phase could result from a cessation of accretion or from a weakening of the surface magnetic field, if it were primordial, or other factors. The correlation between IR excess emission and rotation period shown by Edwards et al. (1993) strengthened the argument for disk regulation. The enlarged data set and analysis presented here provides further support for this scenario, as we now discuss.

The strongest argument in favor of disk locking is the bimodal period distribution of stars more massive than 0.25 $M_{\odot}$ (Figure 8). This is now established both qualitatively and quantitatively. The gap is a result of the rapid period evolution of young PMS stars which are conserving angular momentum. Figure 14 clearly shows how rapidly a star with M > 0.25 $M_{\odot}$ will reach a period near 2 days under those circumstances. The peak at 2 days is populated with stars which have contracted under angular momentum conservation from somewhere near their starting points in the DM94 tracks or, equivalently, from the birthline (Stahler, 1999). The existence of a peak near 8 days is difficult to understand without recourse to the disk-locking mechanism. As CH pointed out, models such as those of Ostriker & Shu (1995) naturally yield a disk-locking period of about 8 days for reasonable values of the parameters. As far as we are aware, no other theory of rotational evolution can account for the period distribution either quantitatively or qualitatively. Since stars of all masses would be expected to pass through the 8 day period regime in very quick order (cf. Fig. 14), the existence of the peak in the frequency distribution at this period indicates that some sort of period regulation mechanism must be operating.

Johns-Krull, Valenti & Koresko (1999) have recently calculated the average stellar magnetic field, B (at the magnetic equator), required by disk-locking models given observed masses, radii, mass accretion rates and rotation periods for T Tauri stars. Following them (and CH) we calculated B for the ONC stars, using masses and radii from Hillenbrand (1997), rotation periods from this study, and assuming a uniform mass accretion rate ($\dot{M}$) of 10^{-8} $M_{\odot}$ yr^{-1}. We adopt the model of Ostriker & Shu (1995) but, as Johns-Krull, Valenti & Koresko (1999) show, the models of Königl (1991) and Cameron & Campbell (1993) give similar results to within a factor of two. In our case,

$$B = 1068\frac{M^{5/6}P^{7/6}}{R^3}$$

where B is in Gauss, M and R in solar units and P in days. The results are plotted in Figure 15 as a function of rotation period. For clarity, the figure was cropped such that a few stars with very large values of B (up to 13 kG) are not shown. They are stars with particularly small radii. The important point, however, is that a typical star in the ONC, with mass ~ 0.3 $M_{\odot}$, radius ~ 2 $R_{\odot}$ and P $\sim$ 8 days, requires B $\sim$ 500 Gauss for disk-locking if the mass accretion rate is what we assumed. Since B $\propto \sqrt{\dot{M}}$ this result does not change much if the accretion rate is somewhat in error.

Values of B $\sim$ 500 G for pre-main sequence stars are quite reasonable to assume, even though direct evidence for them is very difficult to obtain. The classical T Tauri star, BP Tau, has a field of 2.6 ± 0.3 kG according to Johns-Krull, Valenti and Koresko (1999). The existence of spots on the ONC stars implies locally strong fields capable of either channeling accreting matter onto hot spots or disrupting convection to cause cool spots. On the Sun, the field in dark spots is $\sim$ 1-4 kG. If the field on the ONC stars is also concentrated into (two polar) dark spots, we would expect similar field strengths, since the filling factor for the spots is $\sim$ 10 - 30% based on the photometric amplitudes. We conclude that the disk-locking models are quantitatively reasonable in their magnetic field and accretion rate requirements.

4.3. Differences Between Our Study and That Of SMMV

SMMV recently studied the rotation period distribution in and around the ONC and obtained results which are in marked contrast to those reported here. In particular, they found no evidence for a gap in the period distribution and no correlation between rotation period and IR excess emission. This led them to question the observational basis for the disk locking hypothesis. They concluded, in conservative style, that they did not find evidence that disk locking is the dominant mechanism in angular momentum evolution during the PMS phase. In this section we discuss the differences between our work and theirs which, we believe, lead to different results and conclusions.

There are a variety of selection effects which result in differences between our sample of stars with rotation periods and that of SMMV. First, their study includes a much larger area around the ONC than ours. In fact, it extends well beyond the boundaries of the ONC as defined dynamically by Hillenbrand and Hartmann (1998) into the region known as Ori Ic, an older subgroup of Ori OBI (Warren & Hesser 1977). Second, they are missing the very center of the ONC - the region of the Trapezium cluster - because of problems with nebulosity. Third, their images are a bit deeper than ours, leading to better signal to noise for the fainter stars at the expense of saturation of the brighter ones. This results in their having probed a different mass range than is the case for us. For example, only 46% of the stars in their sample for which they give masses have M $>$ 0.25 $M_\odot$, while 61% of the stars in our sample fall into that mass range. They also have no stars with M $\geq$ 0.9 $M_\odot$ whereas 17% of our sample is more massive than that. Finally, while their total sample of stars in Ori OBIc and OBId is 254 stars, the portion of the sample which is inside the defined boundaries of the ONC is only 104 stars, and the number of those with M $>$ 0.25 $M_\odot$ is only 52 stars. Therefore, the fraction of their sample which should show bimodality according to our results could be as low as 20% (i.e. 52/254), whereas in our sample it is 61%. This may be why bimodality is readily apparent in our data set, but less so in theirs.

In addition, there are differences in the observational material and its analysis which affect the samples. Their study was conducted over a period of, at most, 17 days and, in some regions less. They believe that incompleteness in their periods begins at about 8 days. Our observations span $\sim$ 150 days in each of the 8 epochs so we have no incompleteness at long periods. We also

have multiple observations per night, so we are sensitive to short periods as well. However, SMMV do have the advantage of observations at different longitudes, making them less susceptible to the beat phenomenon associated with a one day observing interval. A very important difference, we believe, is that 82 of our 134 periods are "multi-epoch", which helps us define a subset of the data in which the chance of there being "false alarms" is miniscule. The percentage of the SMMV sample which is actually false alarms is expected to be about 10%, assuming that their method of estimating FAP is accurate. (That is, in a sample of 2279 stars which they searched for periods, about 23 would produce light curves, by chance, which had FAP < 0.01. This represents about 10% of the $\sim$ 230 stars with actual periods.) In fact, if their FAP calculation is optimistic, the false alarm pollution could be higher. With only single epoch data there is no way to check these results at the present time, but an observational program to extend the Wesleyan studies to a larger area around the ONC is underway.

Given the selection effects, it is not hard to account for the different conclusions regarding the actual bimodality of the ONC period distribution. Based on this study, we would only expect to find a bimodal distribution in that subset of the SMMV data which has M > 0.25 $M_{\odot}$ and is as young as a typical ONC member, which could be only 20% of their sample, as mentioned above. Do we, in fact, find a bimodal distribution in the portion of the SMMV data set where it is expected according to our results? In Figure 16 we show the period distribution for the 52 stars in the SMMV sample that are within the boundaries of the ONC described by Hillenbrand (1997) and are more massive than 0.25 $M_{\odot}$. The distribution is obviously bimodal and entirely consistent with the results presented earlier in this paper. The solid portion of the histogram indicates those stars from the SMMV sample which have confirmed periods from this study. Clearly there is no conflict in results. Both our data and the SMMV data indicate a bimodal distribution for ONC members with M > 0.25 $M_{\odot}$.

The fact that our entire sample continues to show bimodality, as did the samples analyzed by AH and CH, while the SMMV sample does not (at least as clearly), is a consequence of the different selection effects mentioned above. In particular, their full sample of 254 stars definitely has a greater proportion of low mass stars than ours and probably has many more older stars from the Ori Ic subgroup. They are also missing the youngest portion of the ONC (the Trapezium cluster) and are incomplete for stars with periods exceeding 8 days. Finally, they have a false alarm contamination of at least $\sim$10%. All of these factors tend to diminish the appearance of bimodality in the SMMV total sample relative to the VVO sample.

The fact that SMMV failed to find correlations of period with IR data (or CaII) is a result of the same selection effects discussed above plus lack of a large enough sample size. Again, when we compare similarly selected sub-samples we find no disagreement between the results indicated by the two studies. In particular, for SMMV stars with M > 0.25 $M_{\odot}$ Spearman rank-order tests indicate correlation coefficients that are about the same as what were found by us and the least squares fits indicate identical slopes to within the errors. The main difference is that the significance of the correlations and slopes is much less for the SMMV data on account of their

smaller sample size (about 46 stars compared to our 69) and the fact that they have a smaller range in period (less than 12 days). Including the ∼20 stars in the SMMV sample with IR excess and/or CaII data which were not already in our sample has very little effect on the correlations or significances shown in Table 4. We conclude, once again, that there is no conflict between our data sets.

We take this opportunity to comment on two other aspects of the SMMV paper which relate to the disk-locking hypothesis. First, in their Figure 15, SMMV show a correlation of period distribution with "age". Age is placed in quotation marks because it is highly model dependent and, as Hillenbrand (1997) has noted, likely to be unreliable for values less than 1 Myr owing to the neglect of the birthline in the DM94 models (cf. Palla & Stahler 1999). In fact, the ages derived by Hillenbrand (1997) are mass dependent, as she discussed and we show in Figure 17 for the mass range relevant to the SMMV sample. Rather than sorting the stars by age, we believe that SMMV have actually (inadvertently) sorted the stars by mass. Their sample labeled log age < 5 consists almost exclusively of stars with $M \leq \sim 0.3\ M_{\odot}$, whereas their sample labeled log age > 5.7 contains stars with the full range of masses. Our interpretation of their Figure 15 is that it says nothing about the evolution of period with age, since the age is not accurately measured by the plotted quantity. But it does reflect the same trend of period with mass displayed in our Figure 8, namely, the higher "age" (mass) sample appears bimodal while the lower "age" sample is more uniform.

Our second comment on SMMV results refers to their discovery of stars rotating at or near critical (breakup) velocity in the ONC. Although these short periods and the membership of the stars must be confirmed, it is not clear to us why SMMV regard them as posing a serious challenge to the present picture of rotational evolution. The evidence for disk locking discussed here relates to an event which happens in the first ∼ 1 Myr of the star's evolution. As Figure 14 demonstrates, this is the critical time to impact the spin-up of the star, since this is when the radius is changing most rapidly. If some stars emerge from their protostellar stage spinning at critical velocity and are not subsequently slowed by interaction with a disk, then they may end up on the main sequence spinning at nearly critical velocity as well. Of course, the well known mechanism of angular momentum loss through magnetized stellar winds will act, on the longer timescales of PMS contraction, to drain some angular momentum. Therefore, as the star contracts, it will remain at, or near, critical velocity but this poses no problem to a picture of rotational evolution which involves disk-locking in the first few Myr for many (but, of course, not all) stars. In fact, if all stars were disk-locked we would be unable to understand the wide variation in rotation periods observed in the ONC or in the Pleiades. So the existence of stars with very short periods is in no way a challenge to the standard scenario of rotational evolution which involves a brief, but important, disk-locking phase as well as wind losses on a longer time scale. Of course, the evolution of a star which is rotating at critical velocity and still contracting is an interesting theoretical issue. Perhaps such a star will be surrounded by an extruded disk analogous to those seen in Be stars and perhaps these could, on occasion be mistaken for accretion

disks.

5. Summary and Conclusions

Eight years of monitoring stars in the ONC has led to the determination of 134 rotation periods, 82 of which are confirmed in multiple seasons. We find that rotational properties depend on mass. Stars more massive than 0.25 $M_{\odot}$ have a bimodal distribution with a significant gap near 4 days, while less massive stars have a narrower distribution without a gap. The difference can be understood in terms of stellar evolution. Lower mass stars with ages $\sim$ 1 My are undergoing significant deuterium burning which keeps them more inflated and, hence, spinning slower than the more massive stars. The bimodal distribution for the more massive stars, which was discovered by AH and confirmed by CH, but questioned by SMMV, is established here both qualitatively and quantitatively. Differences between our results and those of SMMV can be understood in terms of selection effects.

Our data provide new observational support for the importance of disk-locking in the angular momentum evolution of stars during their first 1-2 million years. The strongest evidence is the bimodal distribution itself. In the absence of a controlling factor such as disk-locking, PMS stars more massive than 0.25 $M_{\odot}$ would rapidly spin up to periods of 2 days or shorter, unless their initial rotation periods from the proto-star phase were incredibly long ($\geq$ 40 days). The magnetic locking models of Königl (1991) and Ostriker & Shu (1995) and evolutionary scenarios of Cameron, Campbell, & Quaintrell (1995) account for the 8 day peak in the period distribution with reasonable parameters (e.g. surface magnetic field strengths, accretion rates, etc.) which are on fairly solid observational and theoretical grounds (cf. Johns-Krull, Valenti & Koresko 1999). It is the only theory that makes quantitative predictions of this sort which can be checked by our data. Disk-locking is observed to occur in analagous astrophysical situations (e.g. dwarf novae; c.f. Sion 1999) and it is certainly the leading candidate at present to explain the rotation period data in the ONC and other young clusters.

Some additional evidence in support of disk-locking comes from four weak, but significant, correlations which we find. Rotation period correlates with position in the cluster in the sense that longer periods are concentrated towards the central ("Trapezium cluster") region. Hillenbrand (1997, 1998) showed that this is the youngest part of the ONC and also contains the greatest percentage of stars with disks. Among the stars more massive than 0.25 $M_{\odot}$, we also find that rotation period is correlated with IR excess emission in both I-K and H-K and is anti-correlated with CaII equivalent width. All three findings indicate an association between rotation and accretion disks similar to what was found by Edwards et al. (1993). As discussed by those authors, this evidence supports the idea of disk-regulated rotation.

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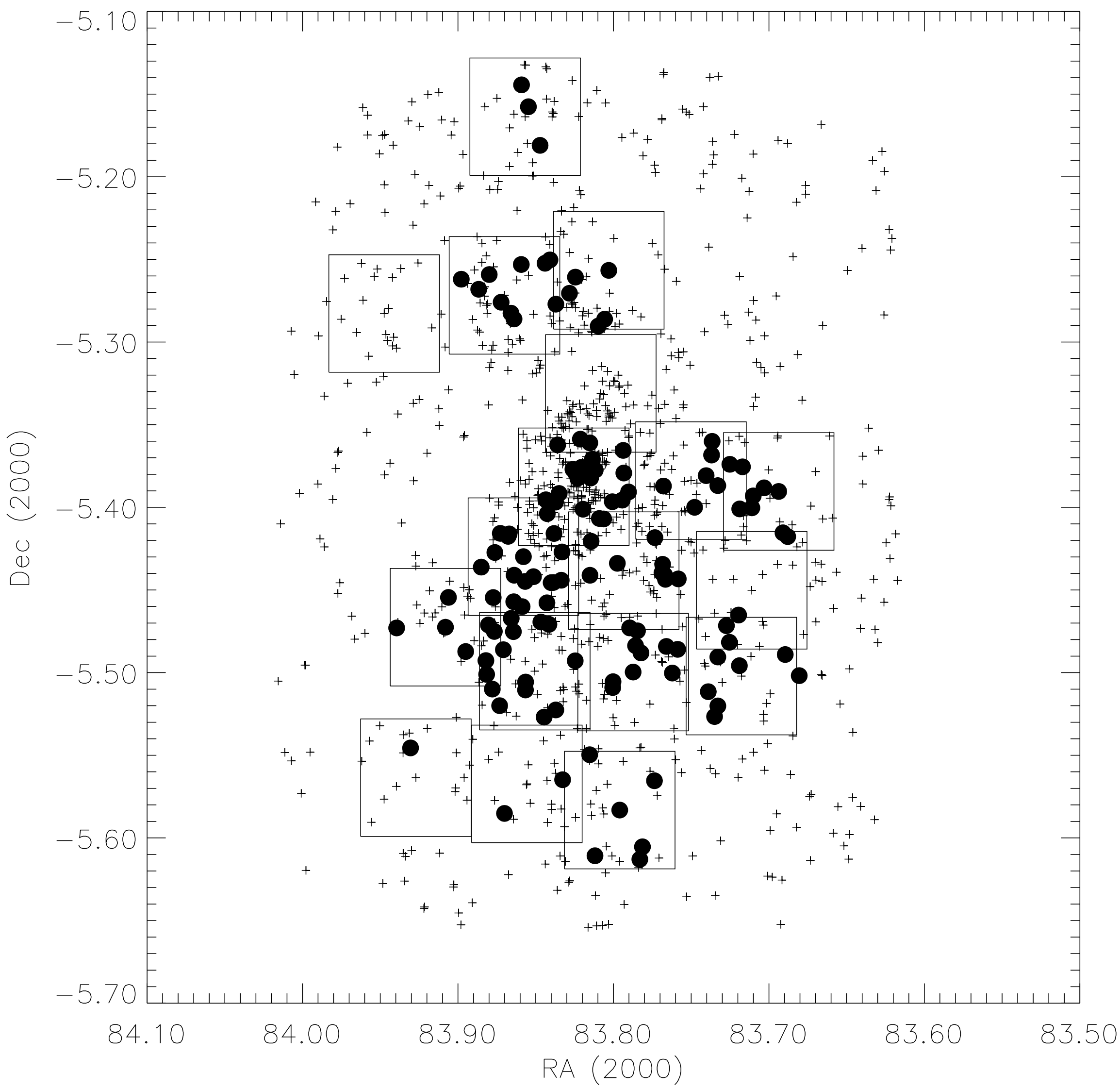

Fig. 1.— The ONC. Stars in the Jones and Walker (1988) catalogue are plotted as plus signs. Stars for which we have determined rotation periods are shown as solid circles. The small rectangles outline the individual fields surveyed at VVO, as detailed in Table 1.

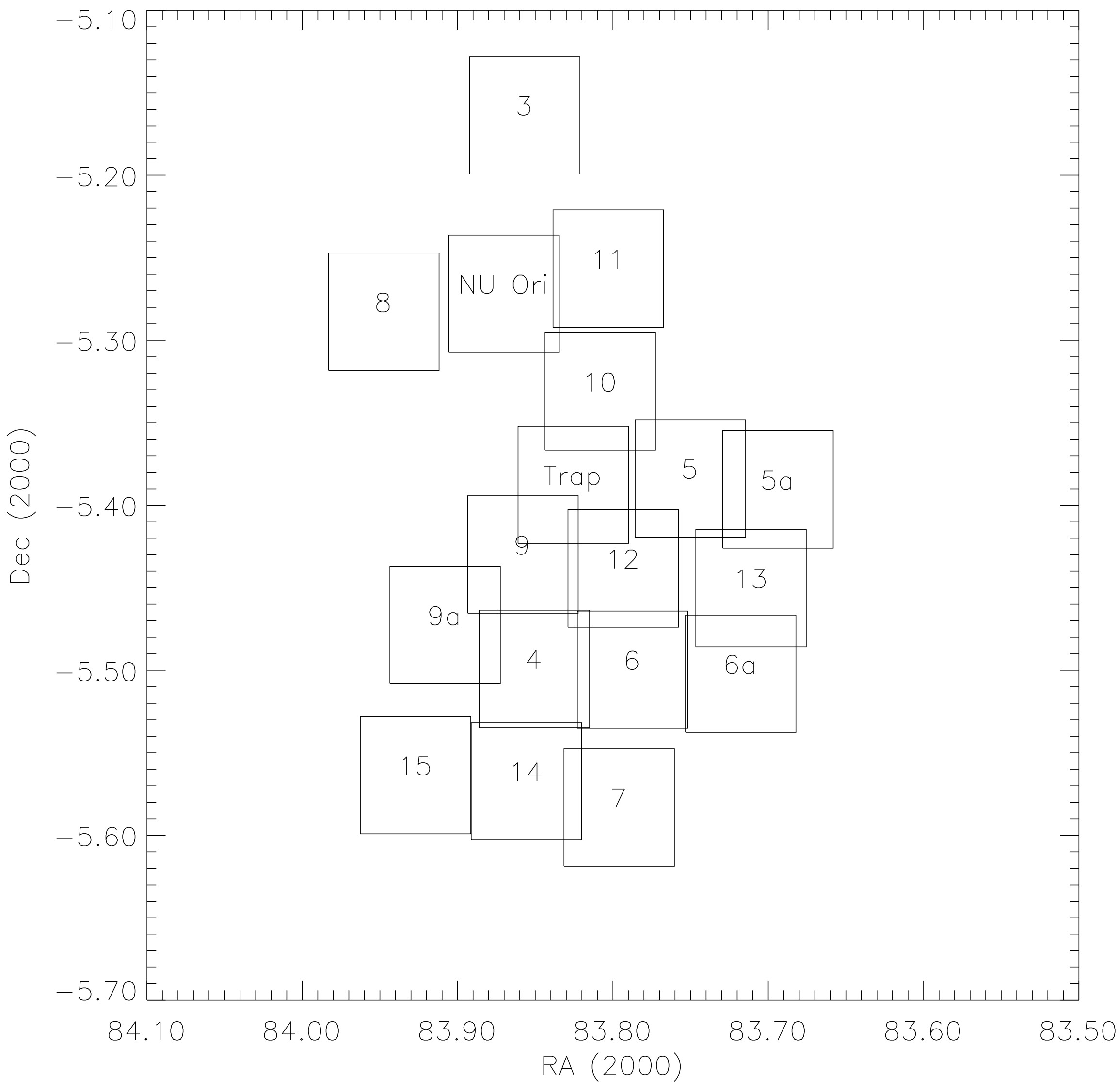

Fig. 2.— The naming scheme for fields observed at VVO. See Table 1 for information on the epochs at which each field was monitored.

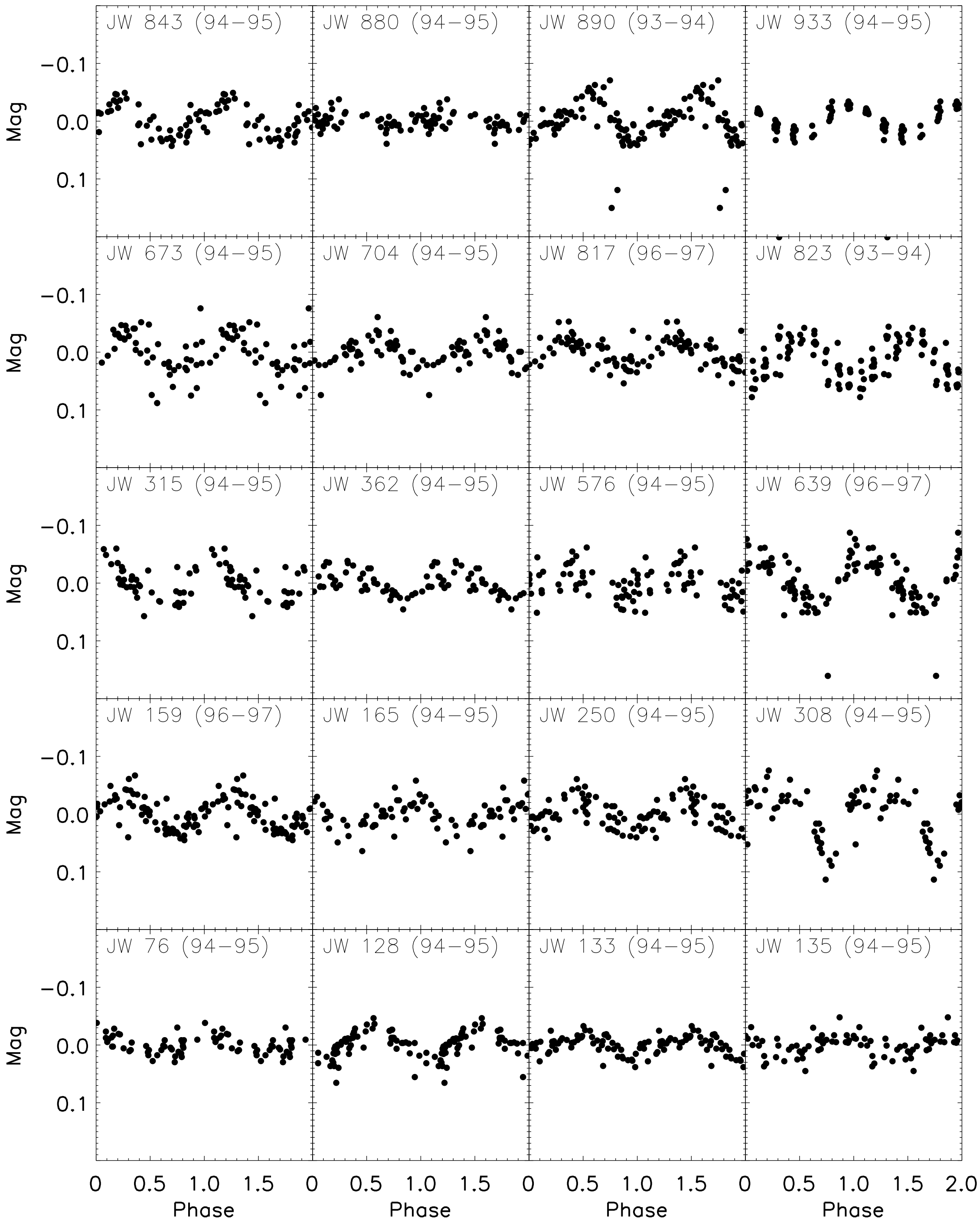

Fig. 3.— Light curves for stars in Table 2 which have not previously been displayed by CH or AH.

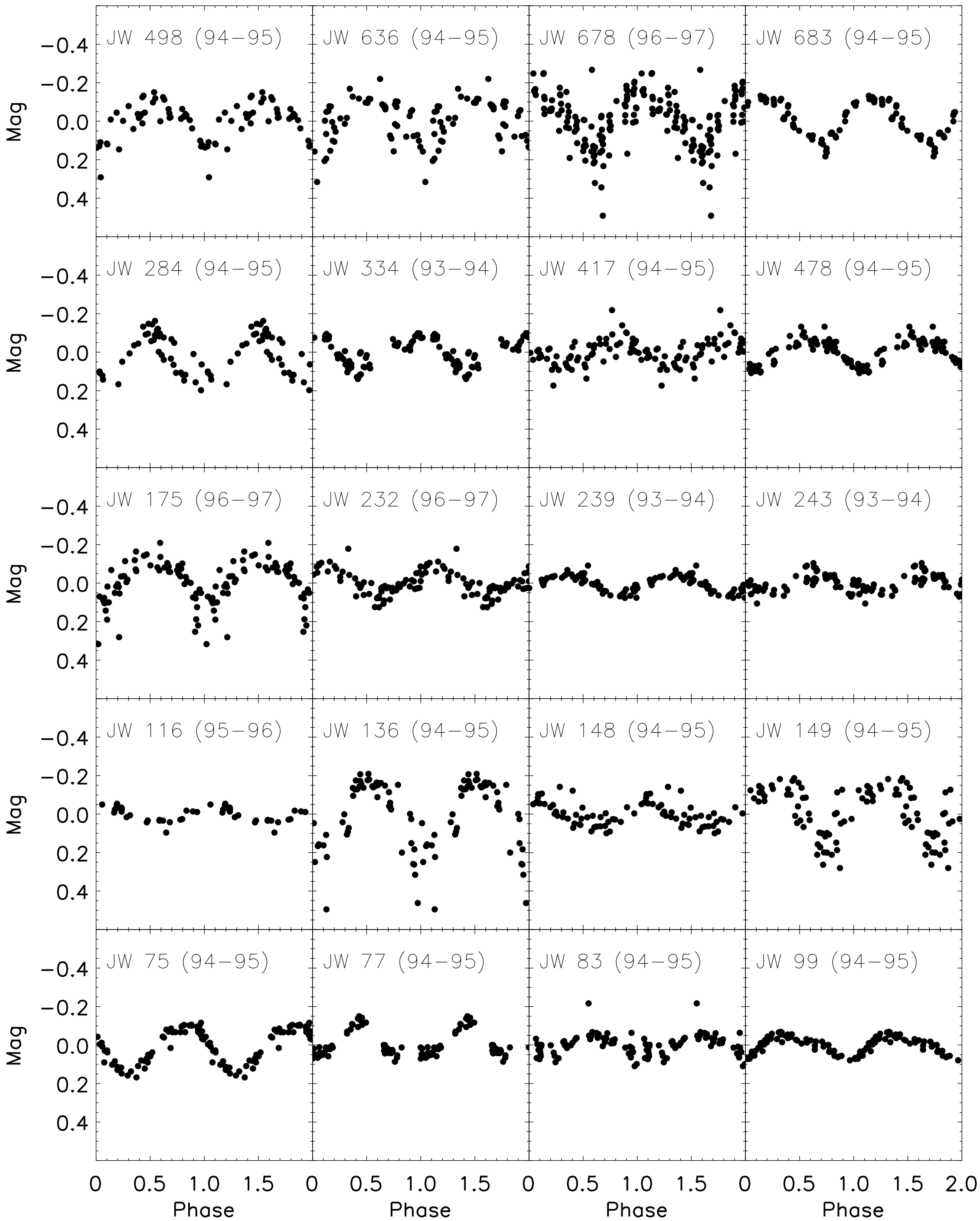

Fig. 3.— Light curves, continued.

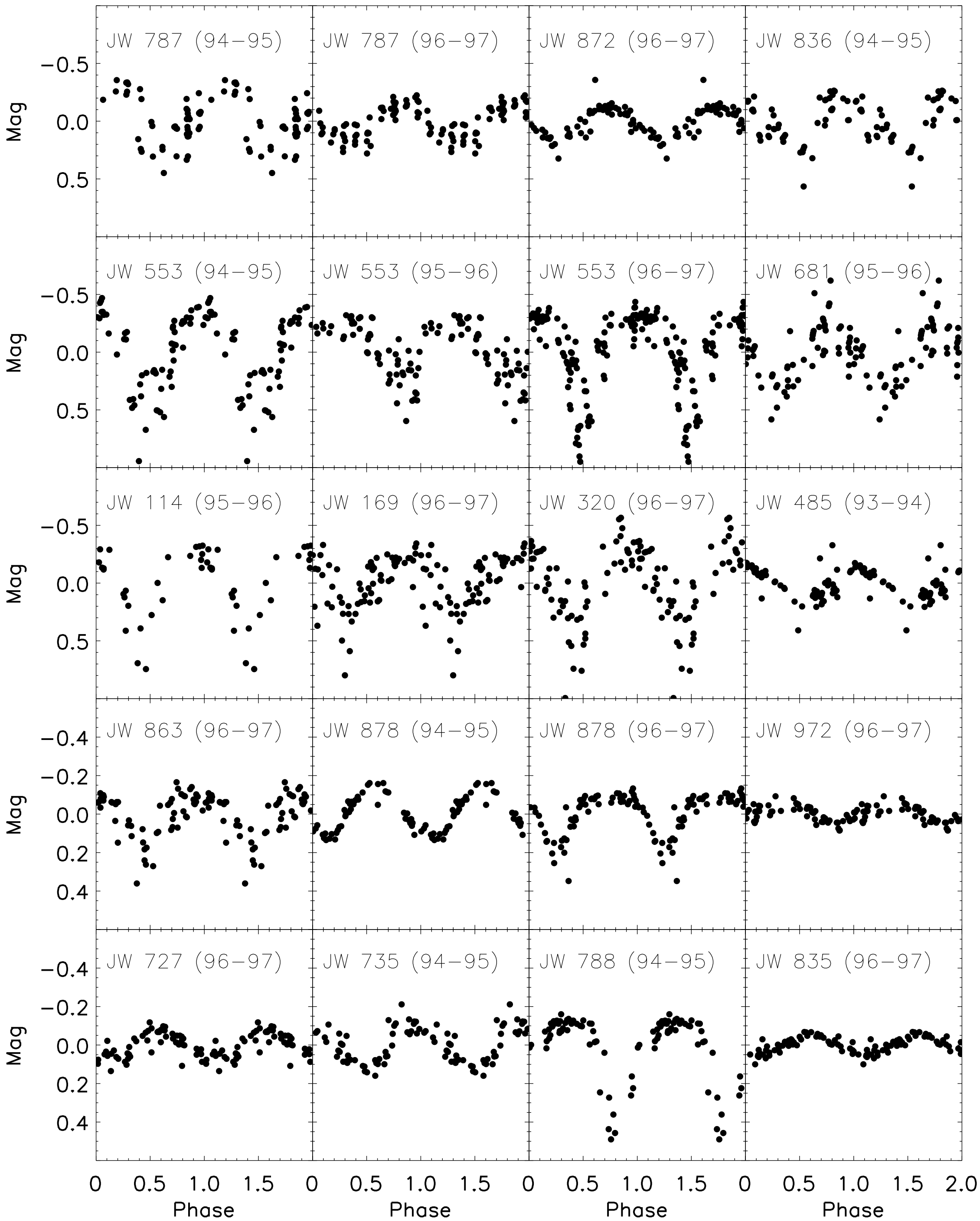

Fig. 3.— Light curves, continued.

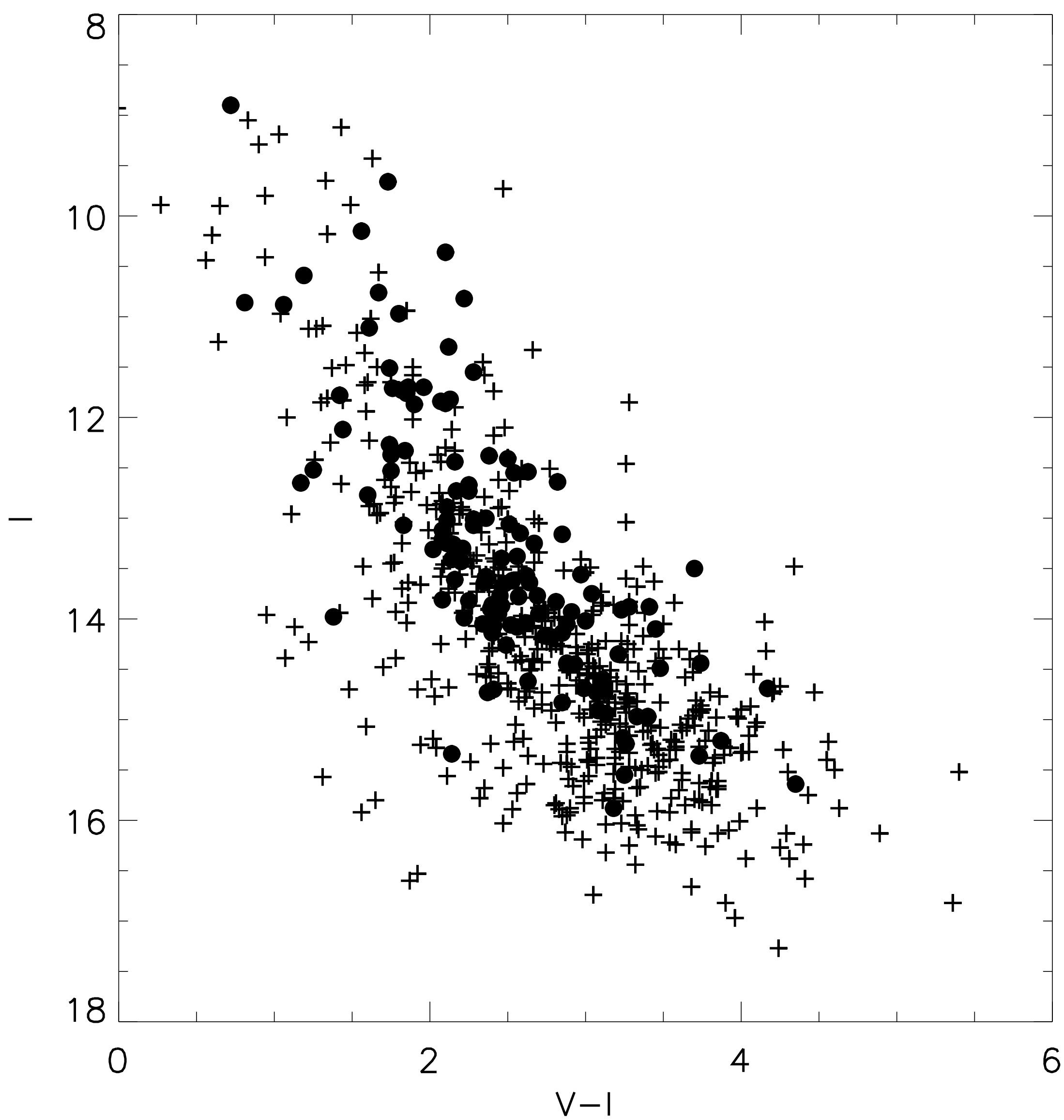

Fig. 4.— Color-Magnitude diagram for JW stars monitored by us. Solid circles indicate periodic stars and plus signs indicate those not found to be periodic.

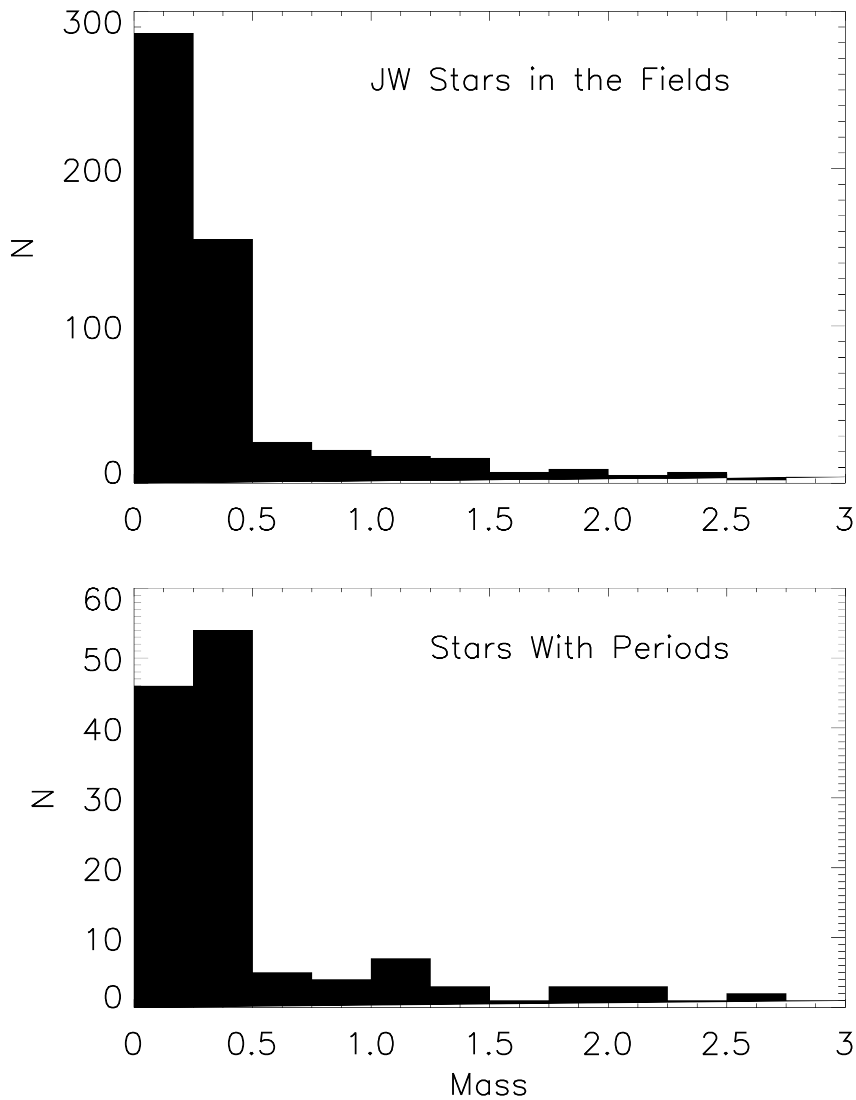

Fig. 5.— The mass distribution for all JW stars in our fields (top panel) and for the stars for which rotation periods have been found (bottom panel).

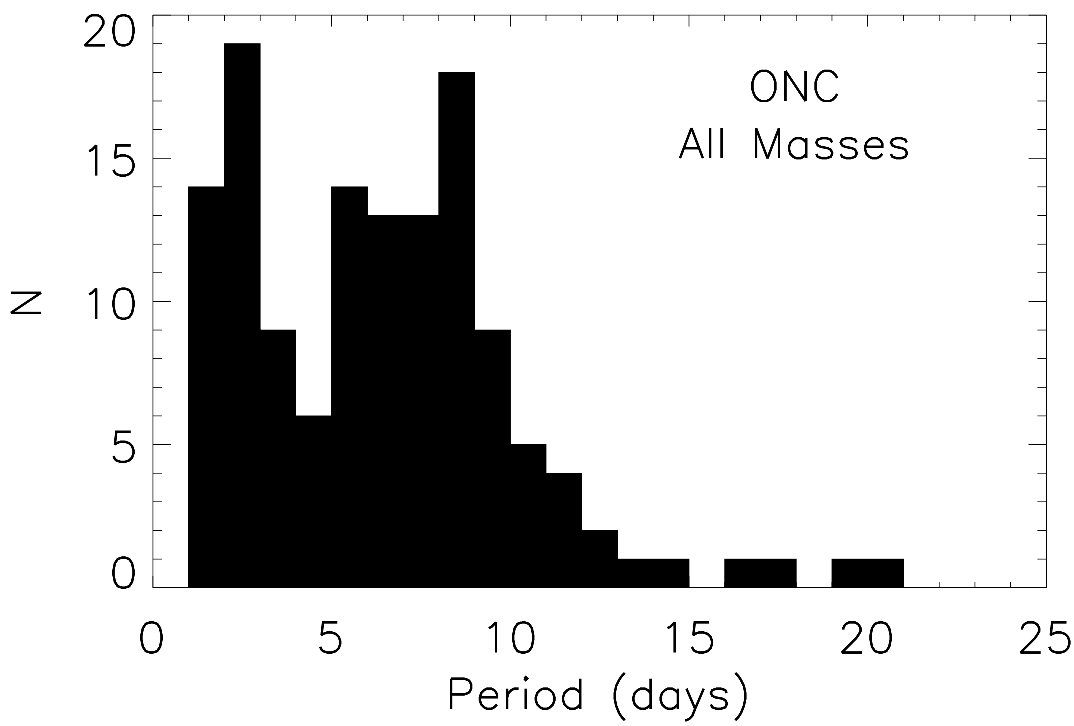

Fig. 6.— The frequency distribution of rotation periods for stars of all mass in the ONC. One star, with a period of 34 days, lies outside the boundaries of the figure.

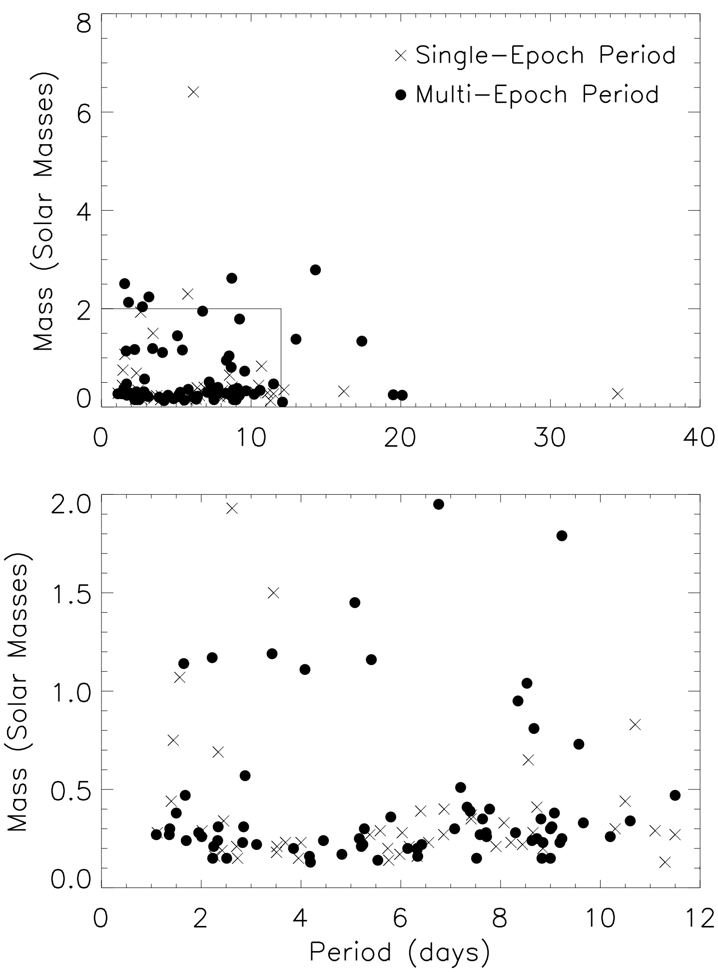

Fig. 7.— Mass versus rotation period. Solid circles are multi-epoch periods; crosses are single-epoch periods. The top panel shows the entire data set and the bottom panel is an expanded view of the boxed region.

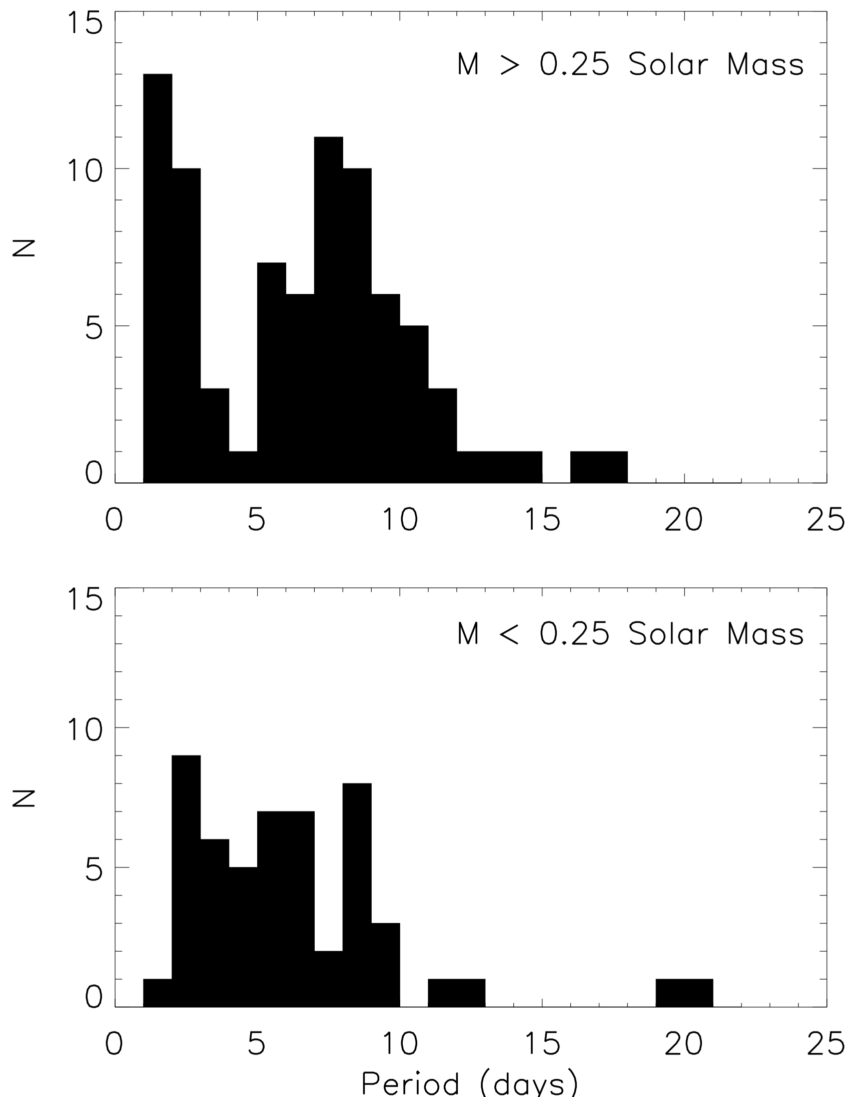

Fig. 8.— Rotation period distributions for more massive stars (top panel) and less massive stars (lower panel).

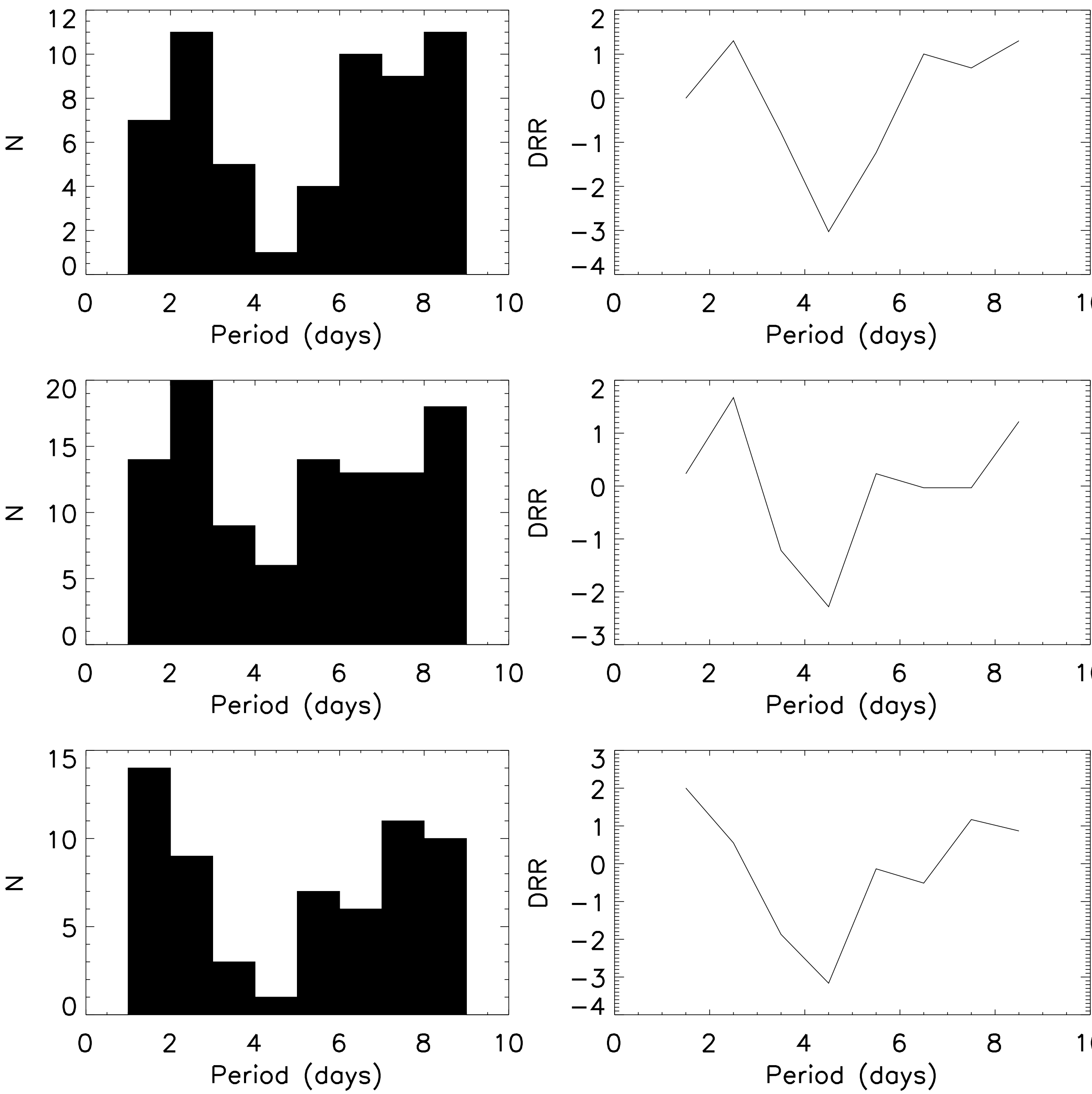

Fig. 9.— Period distributions (right) and DRR test results (left) for three samples: CH (top), all masses (middle), stars with M > 0.25 $M_\odot$ (bottom).

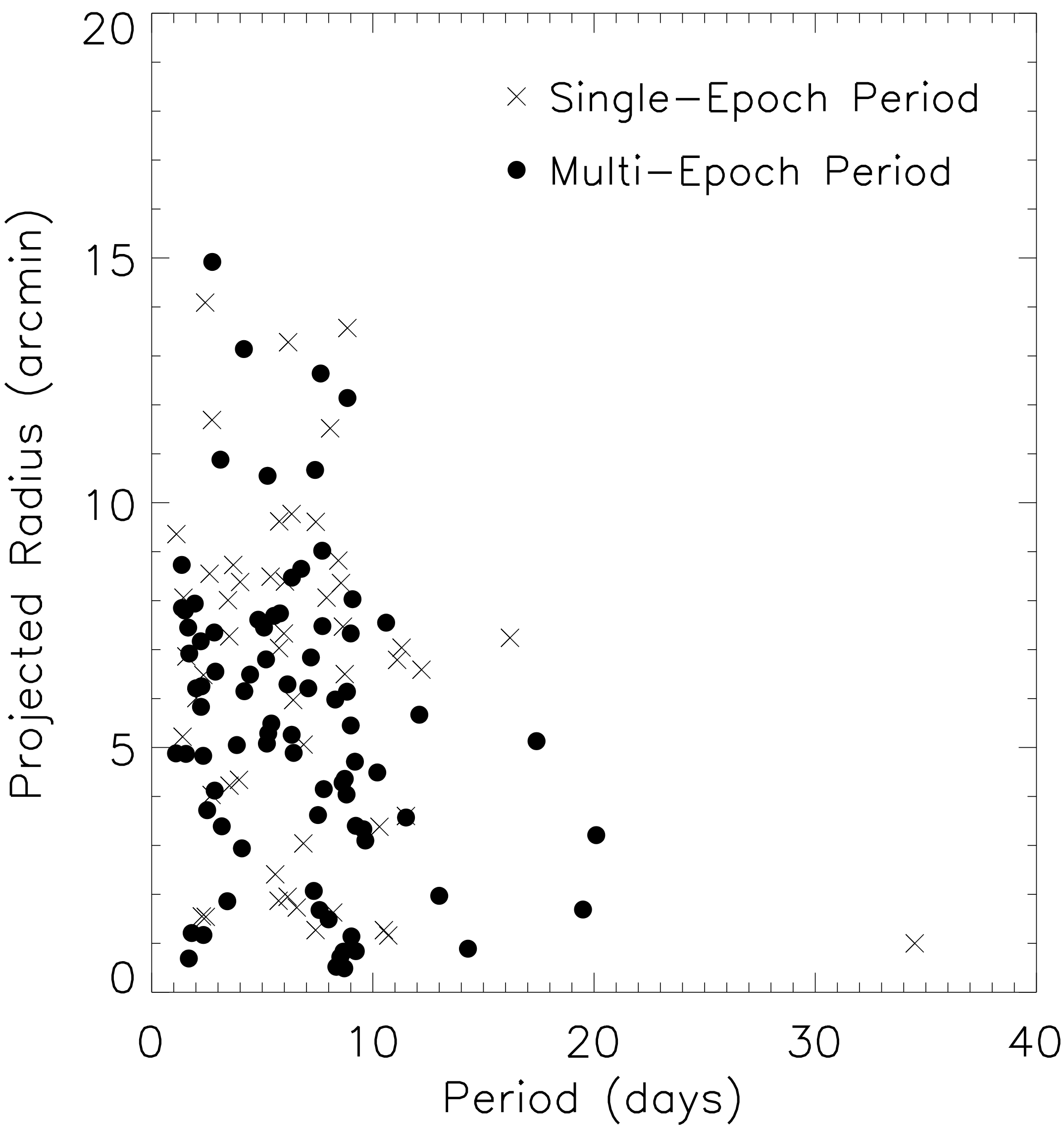

Fig. 10.— Projected Radius (in arc-minutes) from the center of the ONC versus Rotation Period. Solid circles are multi-epoch periods and crosses are single-epoch periods.

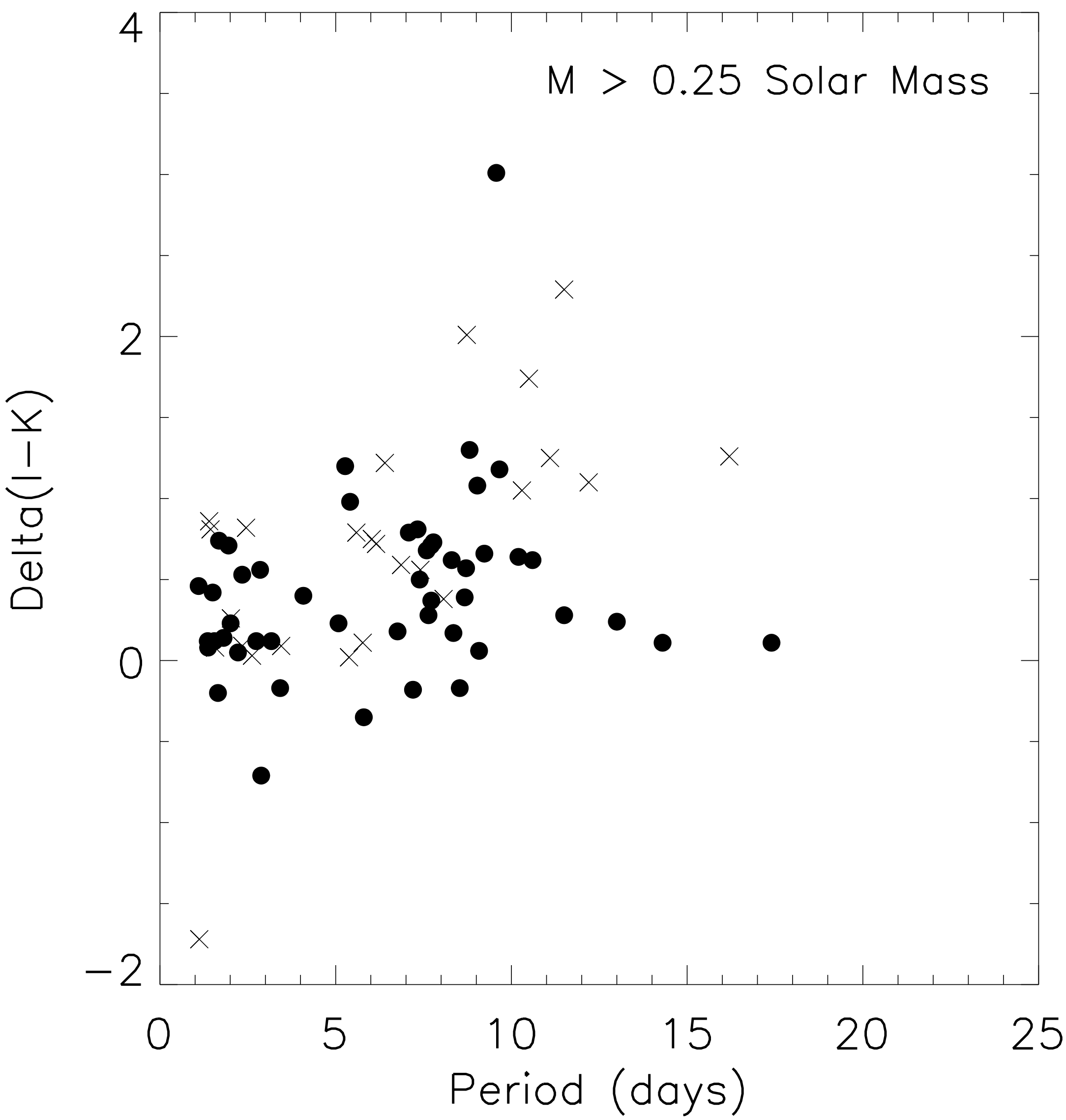

Fig. 11.— Excess I-K emission from Hillenbrand (1997) versus rotation period for stars with M > 0.25 $M_\odot$. Solid circles are multi-epoch periods and crosses are single-epoch periods.

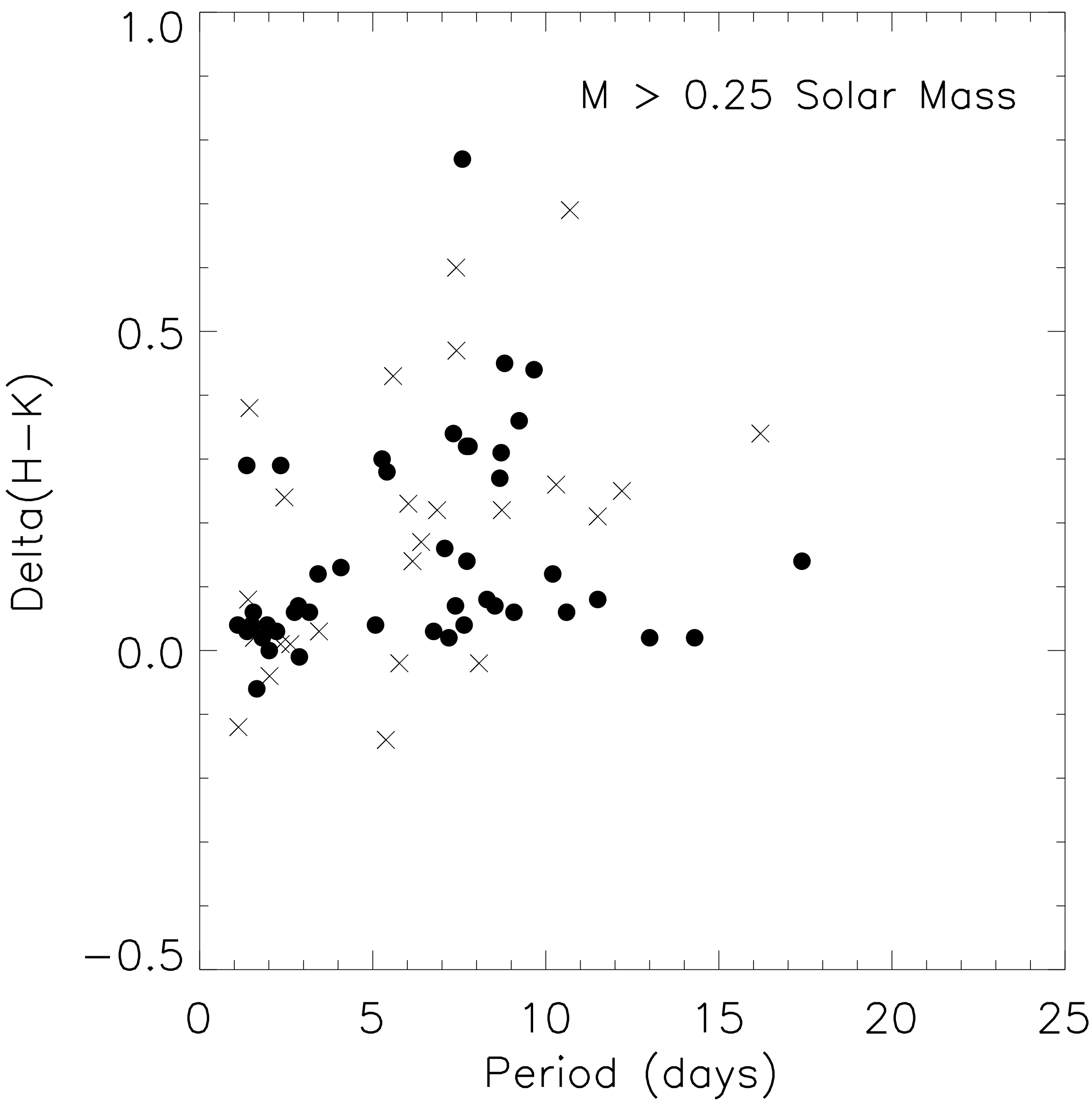

Fig. 12.— Excess H-K emission from Hillenbrand (1999) versus rotation period for stars with M > 0.25 $M_{\odot}$. Solid circles are multi-epoch periods and crosses are single-epoch periods.

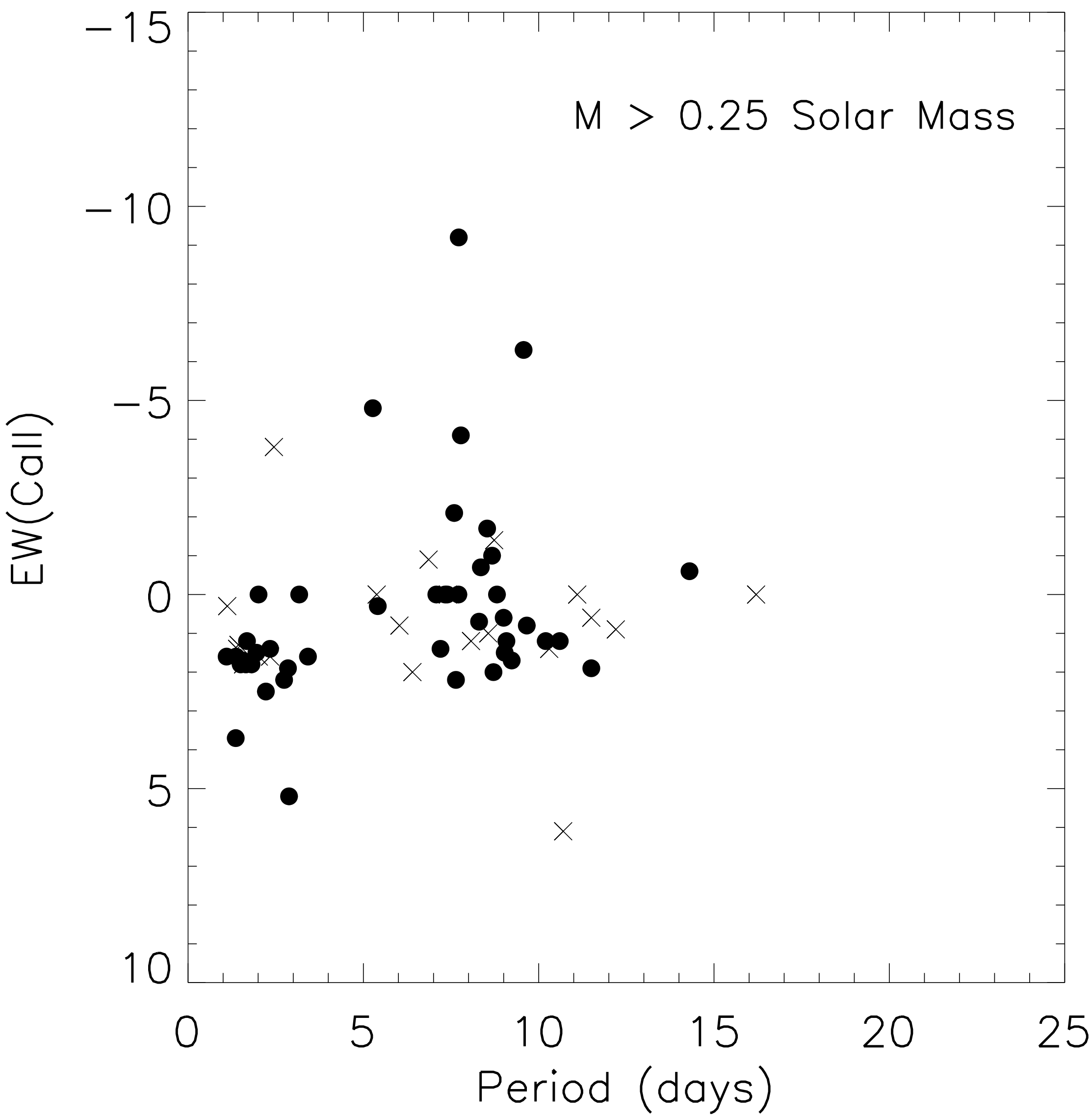

Fig. 13.— Equivalent width of Calcium II emission from Hillenbrand (1997) versus rotation period for stars with M > 0.25 $M_{\odot}$. Solid circles are multi-epoch periods and crosses are single-epoch periods.

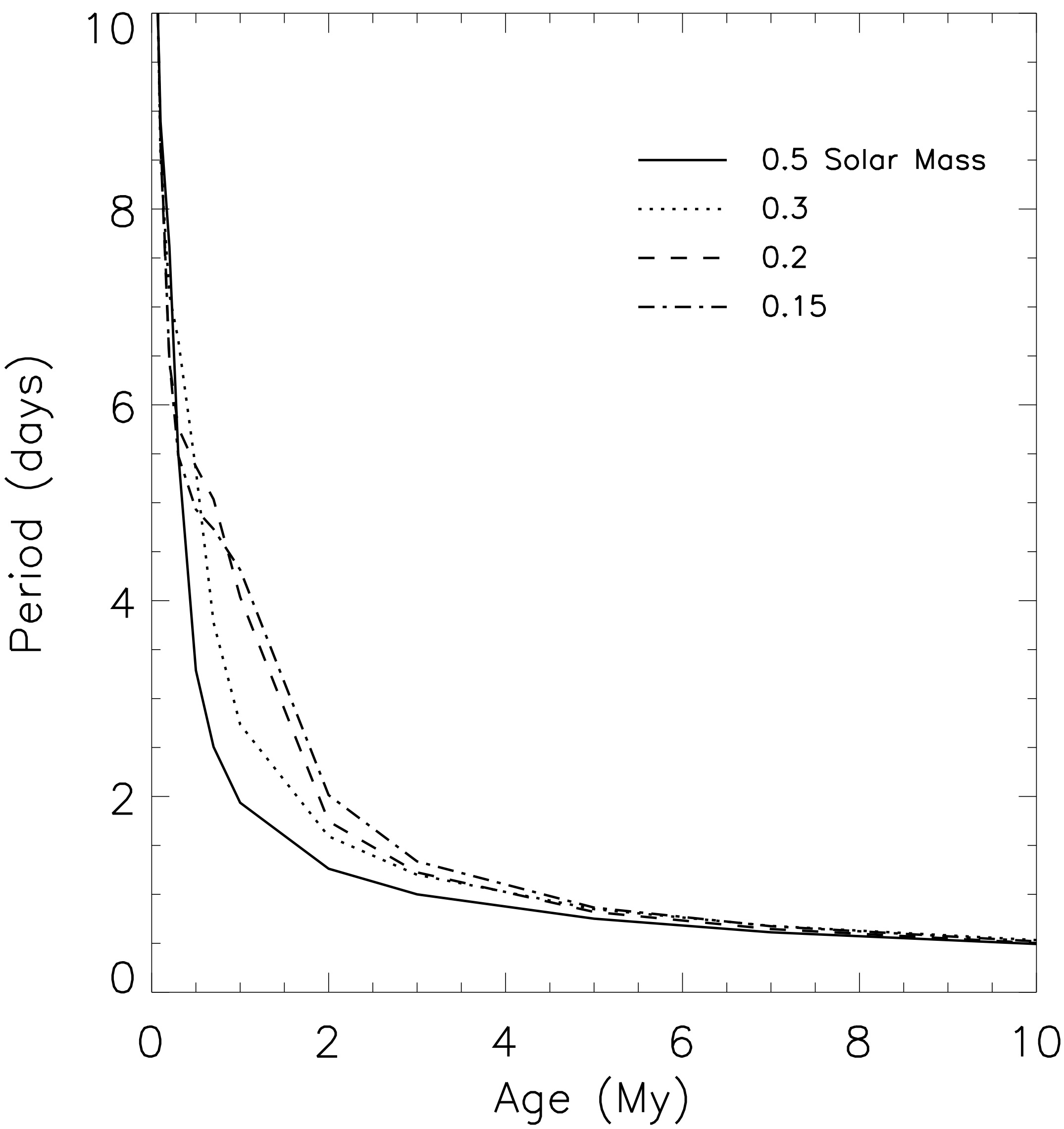

Fig. 14.— The variation of rotation period with time for stars of different masses, based on the models of DM94. The starting point is a period of 10 days at an age of 0.07 My.

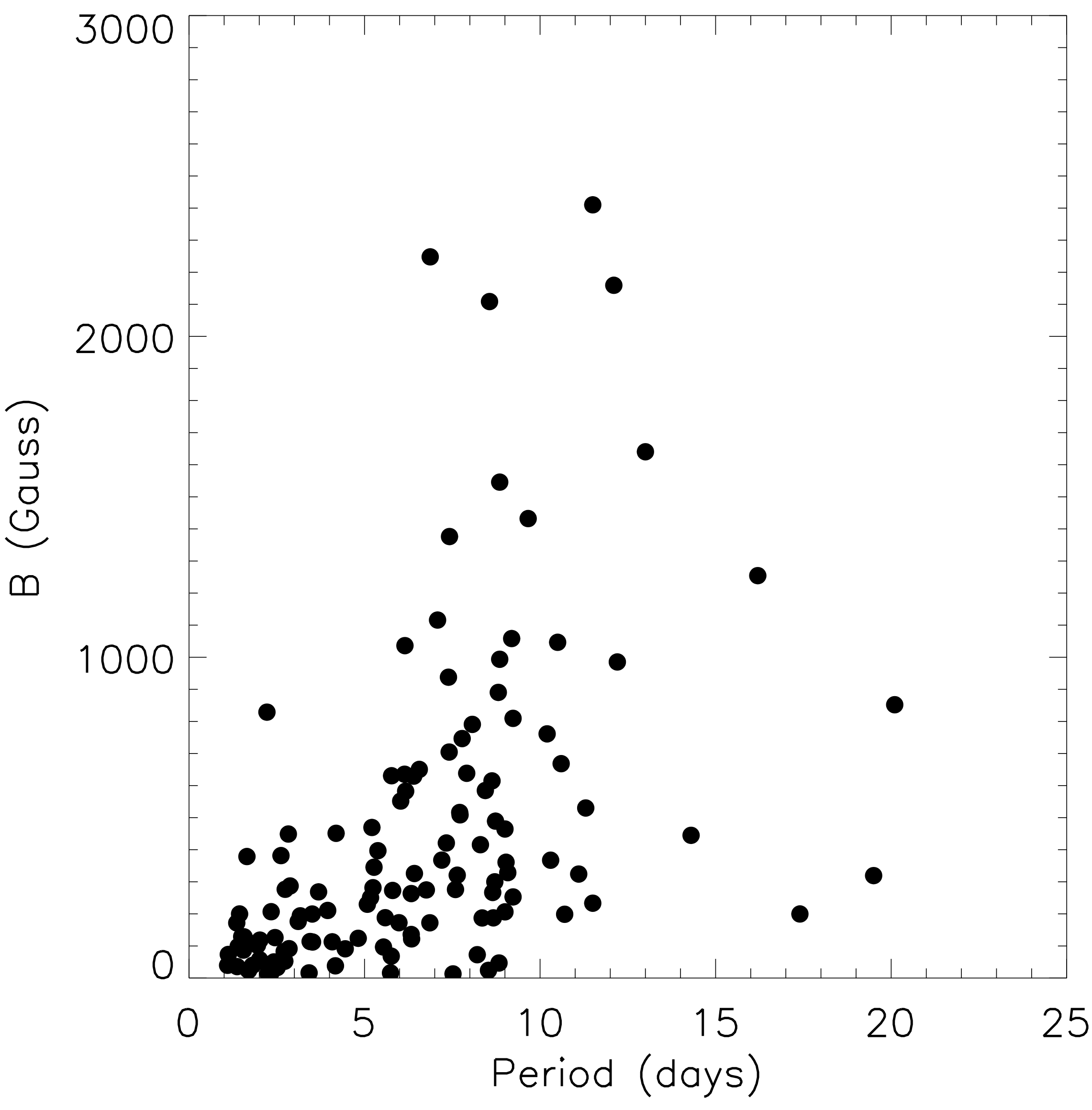

Fig. 15.— The mean equatorial magnetic field strength, B (in Gauss), predicted by the disk-locking theory of Ostriker and Shu (1995) assuming a mass accretion rate of $10^{-8}\dot{M}_{\odot}yr^{-1}$ versus rotation period.

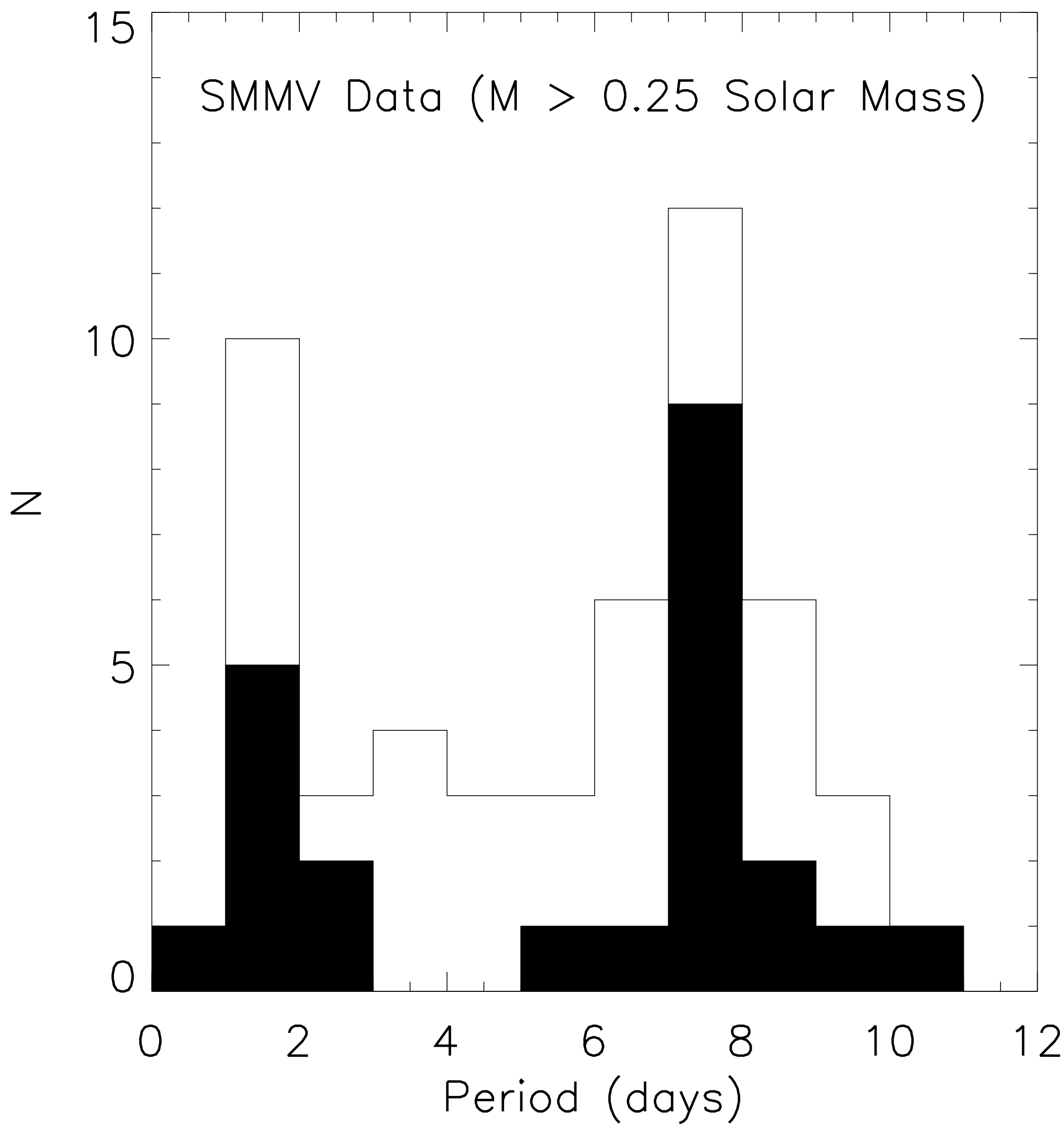

Fig. 16.— The frequency distribution of stars with M > 0.25 $M_\odot$ and rotation periods determined by SMMV. The solid portion of the histogram is for stars whose rotation periods are confirmed in this study.

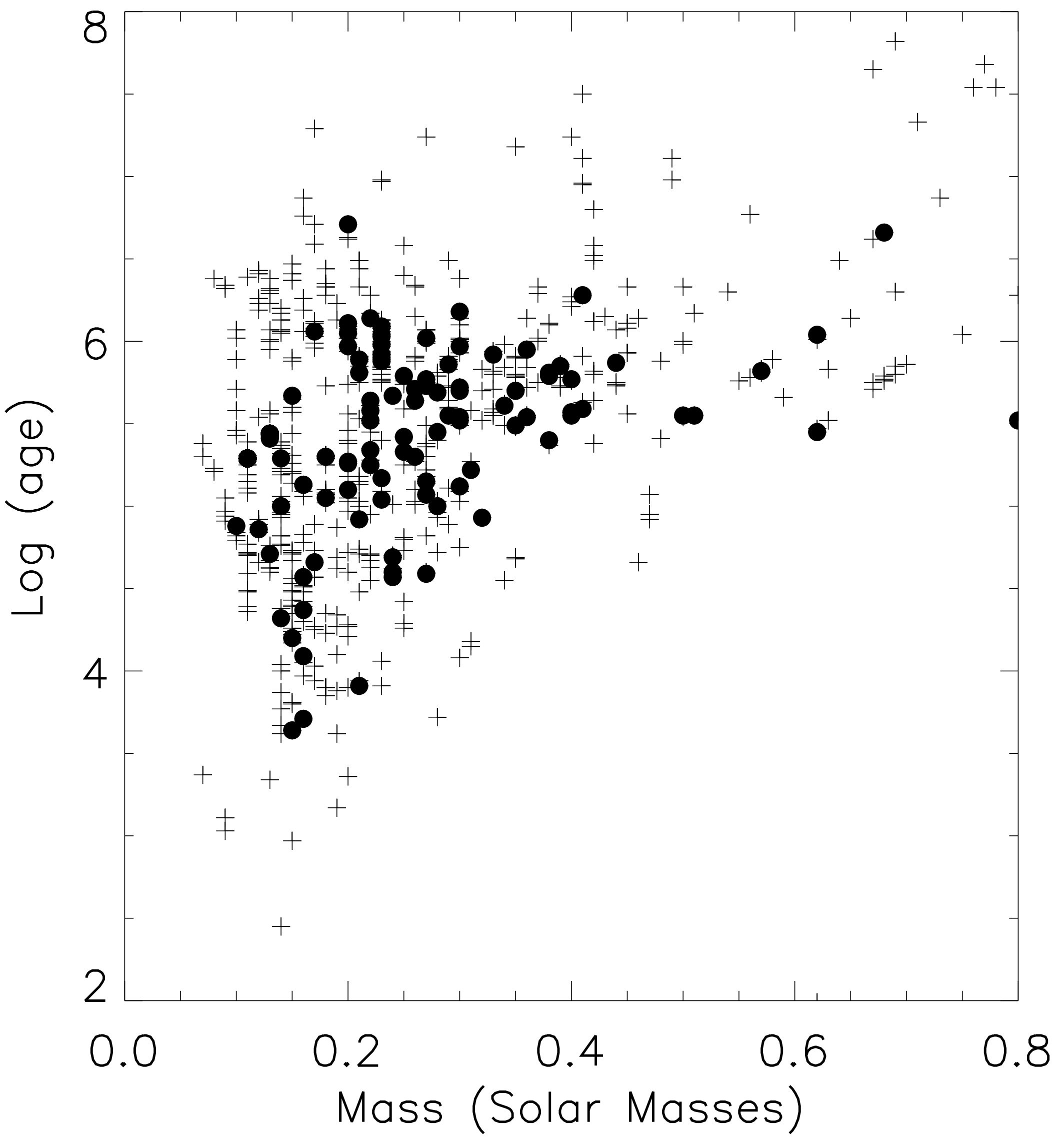

Fig. 17.— Age, as determined by Hillenbrand (1997) based on the models of DM94, versus mass. Plus signs are JW stars without known rotation periods. Solid circles are stars with periods from SMMV. This figure illustrates the correlation that exists between "age" and mass in the samples studied by SMMV.

Table 1. Field Names, Central Stars and Epochs of Observation

Field	Central Star	90-91	91-92	92-93	93-94	94-95	95-96	96-97	97-98	N[a]	N(JW)[b]
Trapezium	582	X	X	X	X	X	X	X	X	126	115
NU Ori	834		X	X						50	36
Ori 3	779		X	X						30	20
Ori 4	753		X			X	X	X		62	51
Ori 5	193		X	X	X	X	X	X		52	46
Ori 5a	83					X	X			34	28
Ori 6	330		X	X	X	X	X	X		39	33
Ori 6a	132			X		X	X	X		30	23
Ori 7	362		X			X	X			31	26
Ori 8	997		X							27	18
Ori 9	792		X	X	X	X				55	40
Ori 9a	933			X	X	X				34	31
Ori 10	429		X							72	58
Ori 11	388		X	X						48	31
Ori 12	348			X	X	X				61	48
Ori 13	117					X	X			31	20
Ori 14	781							X		28	24
Ori 15	966							X		19	17

[a]The number of stars monitored in the field.

[b]The number of JW stars monitored in the field.

Table 2. Periods For Stars in the ONC

JW	90-91	91-92	92-93	93-94	94-95	95-96	96-97	97-98	98-99	Adopt	SMMV
65			7.44		7.34					7.39	7.04
75					3.45					3.45	
76					6.33					6.33	
77					1.50	1.50				1.50	1.50
83					7.72					7.72	7.40
99					1.70	1.70				1.70	1.69
114						8.73				8.73	
116						2.34				2.34	
128					8.83					8.83	8.35
133					2.02					2.02	
135					3.69					3.69	
136-137					8.65					8.65	
145		12.15			12.02					12.1	
148					1.37					1.37	1.37
149					2.83					2.83	2.76
157		17.25		17.4	17.6					17.4	
158						1.95	1.94			1.95	1.92
159							1.12			1.12	
165					5.77					5.77	
167			1.40							1.40	
169					3.86		3.83			3.85	3.82
174			1.36		1.36					1.36	1.36
175				9.16	9.24	9.18	9.16			9.19	
191[a]			8.54					8.67	8.69	8.63	8.82
220			2.32	2.33					2.32	2.33	
222			5.17	5.16						5.17	5.06
232							5.09		5.07	5.08	
239		4.46		4.43						4.45	4.44
243				10.2						10.2	10.1
245			8.63		8.83					8.73	9.46
248		6.86								6.86	
250					2.71					2.71	
254			3.52							3.52	
275			20.4	19.8	20.3	20.2	19.8			20.1	
284					3.11					3.11	3.09
308					4.17					4.17	4.20
311		6.14	6.13	6.13			6.15			6.14	6.13
315					8.85					8.85	
320					5.43		5.39			5.41	
326			6.40							6.40	
330		1.57								1.57	
334				5.27						5.27	5.32
337			19.3					19.7		19.5	
345[b]				8.21						8.21	
347	7.31	7.32	7.33	7.38	7.33			7.39		7.33	7.33
352	7.98	7.99	8.03	7.95	7.95	8.11	7.97			8.00	
362					2.73					2.73	
365			4.08						4.09	4.08	
378	9.05	9.01								9.03	
379[c]		5.65					5.59			11.3	11.3
381			16.2							16.2	
388		9.08	9.08						9.10	9.08	7.78
406			2.25							2.25	2.26
417					7.41					7.41	
437			2.33	2.34	2.34					2.34	
439			8.30							8.30	8.35
454		8.69	8.70	8.62					8.66	8.67	
466		6.17								6.17	
470			10.69							10.7	
478					5.74					5.74	

Table 2. (continued)

JW	90-91	91-92	92-93	93-94	94-95	95-96	96-97	97-98	98-99	Adopt	SMMV
479		8.74					8.68			8.71	
481[d]			6.56							6.56	
485				9.63	9.68					9.66	9.46
498					7.42					7.42	
526		1.68	1.69	1.68	1.68				1.68	1.68	
536			9.21	9.24						9.23	
544		3.43	3.43	3.42	3.41	3.42			3.40	3.42	
553					8.39	8.34	8.33			8.35	
559								2.27		2.27	
563			5.80							5.80	6.12
567	8.58	8.53		8.48			8.54		8.52	8.53	
576[e]					2.01		1.08			2.01	
589	14.32	14.32	14.28	14.28	14.38		14.36			14.3	
601		2.22							2.23	2.22	
636					5.59					5.59	
639							5.26		5.22	5.24	5.16
641			3.16	3.18					3.16	3.17	
648[f]				34.51						34.5	
660	6.15									6.15	
664		7.20	7.19						7.23	7.20	7.63
669				1.81			1.81		1.81	1.81	
673					1.44					1.44	
678[g]								13.02	12.93	13.0	
681						10.46				10.5	
683				11.5	11.5					11.5	
691		6.34								6.34	6.29
695		11.53								11.5	
704					6.87					6.87	
710	7.53		7.63	7.60	7.56	7.57	7.65			7.59	7.66
716			3.95							3.95	
717			4.00							4.00	
721[h]				2.45						2.45	
727							6.03			6.03	
731		7.63	7.64							7.64	7.70
735					5.21					5.21	5.21
758		2.51	2.51	2.51						2.51	2.49
765			2.42							2.42	
784-787					8.97		9.04			9.00	7.74
786		8.79	8.80	8.84					8.80	8.81	
788[i]					4.82					4.82	4.76
790		2.74	2.74							2.74	
792		10.33								10.3	
794			2.62							2.62	
795		1.56	1.56		1.54					1.55	
811			11.05							11.1	
813		2.85	2.85	2.84	2.84					2.85	2.84
815		6.45	6.40	6.40					6.52	6.42	6.43
817[j]					4.14		2.23		2.24	2.23	
819			5.76							5.76	
823		9.00		9.00						9.00	
826			9.58	9.59	9.55					9.57	
830		9.26	9.27	9.16						9.23	
835							8.85			8.85	8.64
836					12.18					12.2	
837		10.32	10.77						10.78	10.6	8.69
839		7.55	7.51	7.54	7.49					7.52	
843[k]					5.38					5.38	0.84
850		7.78	7.78							7.78	
855		7.02			7.25		6.97			7.08	7.00
860		6.31	6.35	6.33					6.36	6.33	6.30

Table 2. (continued)

JW	90-91	91-92	92-93	93-94	94-95	95-96	96-97	97-98	98-99	Adopt	SMMV
863							7.91			7.91	
866		6.77	6.75							6.76	
872					4.19		4.20			4.19	
878					5.52		5.55		5.55	5.54	5.51
880					3.51					3.51	
890[l]				1.03					1.16	1.10	
892		8.56								8.56	
907			1.65	1.65	1.65					1.65	1.65
914		7.71	7.71							7.71	
930			2.87	2.88	2.88					2.88	2.79
933					5.98					5.98	
972							8.07			8.07	
984[m]			8.46	8.41						8.44	1.13
H3128[n]				2.47						2.47	

[a] JW 191. A period of 4.33 days with 0.03 < FAP < 0.01 was found in 91-92. This is one-half of the likely true period; presumably the star had spots in two hemispheres during this epoch, similar to what has been observed for V410 Tau (Vrba, Herbst & Booth 1987).

[b] JW 345. There is a large peak in the combined power spectrum (from all seasons) of this star near 21 days.

[c] JW 379. See the text for a discussion of the difference between our result and SMMV.

[d] JW 481. The period possibility near 1.18 days has slightly larger power in the combined power spectrum and could be the true period rather than an alias.

[e] JW 576. Both periods are very close to integral days. We adopted 2.01 days based on the quality of the light curve. Because this is so close to the one day sampling interval, it is particularly uncertain and requires confirmation.

[f] JW 648. Large peaks in the combined power spectra are seen at 3.36 days and 1.42 days and a smaller peak at 34.5 days.

[g] JW 678. This star was first found by combining the power spectra obtained at all epochs, which yielded a large peak at the reported period. It also has an FAP < 0.001 in the 95-96 epoch. It clearly has periodic variation at about that period at three other epochs: 92-93, 93-94 and 94-95.

[h] JW 721. A period of 11.37 days with 0.03 < FAP < 0.01 was found in 91-92.

[i] JW 788. This star has an unusual light curve shape reminiscent of a W UMa star.

[j] JW 817. The period of 4.14 days is inconsistent with v sin i for this star, whereas the 2.23 day period is about what one would predict based on its likely radius and measured v sin i, assuming that sin i is close to 1.

[k] JW 843. A period of 10.88 days with 0.03 < FAP < 0.01 was found in 91-92. Note the similarity to twice the period found in 94-95. See the text for a discussion of the difference between our result and SMMV.

[l] JW 890. A period that close to 1 day would be hard to detect, given our sampling interval. Nonetheless, it may be real, but requires confirmation.

[m] JW 984. See the text for a discussion of the difference between our result and SMMV.

[n] H 3128. This star does not have a JW identification. It is star 3128 in Hillenbrand's (1997) compilation.

Table 3. Masses, Projected Radii, IR excesses and Equivalent Widths

JW	P(days)	Mass($M_\odot$)	R_{proj}($'$)	E(I-K)	E(H-K)	EW(CaII)
65	7.39	0.39	10.7	0.50	0.07	0.0
75	3.45	1.50	8.0	0.09	0.03	
76	6.33	0.16	9.8	0.16	-0.03	1.3
77	1.50	0.38	7.8	0.42	0.04	1.8
83	7.72	0.26	7.5	0.37	0.14	-9.2
99	1.70	0.24	6.9	0.50	0.01	1.4
114	8.73	0.41	6.5	2.01	0.22	-1.4
116	2.34	0.69	6.5	0.09	0.01	1.6
128	8.83	0.15	6.1	0.32	0.02	0.0
133	2.02	0.29	6.0	0.26	-0.04	1.6
135	3.69	0.23	8.7	1.11	0.28	-2.3
136	8.65	0.28	7.5			
145	12.10	0.10	5.7	0.55		
148	1.37	0.30	7.8	0.08	0.03	1.6
149	2.83	0.23	7.3	0.24	0.10	-23.7
157	17.40	1.34	5.1	0.11	0.14	
158	1.95	0.28	7.9	0.71	0.04	1.5
159	1.12	0.28	9.4	-1.72	-0.12	0.3
165	5.77	2.30	9.6	0.11	-0.02	
167	1.40	0.44	5.2	0.86	0.08	1.4
169	3.85	0.20	5.1		0.47	
174	1.36	0.27	8.7	0.12	0.29	3.7
175	9.19	0.23	4.7	0.56	0.32	0.0
191	8.63	0.24	4.3	0.18	0.03	0.0
220	2.33	0.24	4.8	0.67	0.10	1.0
222	5.17	0.25	6.8	0.71	0.11	1.2
232	5.08	1.45	7.4	0.23	0.04	
239	4.45	0.24	6.5	0.38	0.08	1.5
243	10.20	0.26	4.5	0.64	0.12	1.2
245	8.73	0.25	4.4	0.61	0.26	-5.8
248	6.86	0.27	3.0	0.59	0.22	-0.9
250	2.71	0.21	4.0	0.27	0.10	0.9
254	3.52	0.21	4.2	0.50		5.6
275	20.10	0.24	3.2	0.76		1.8
284	3.11	0.22	10.9	1.18	0.41	-2.0
308	4.17	0.16	13.1			0.7
311	6.14	0.20	6.3	0.22		0.0
315	8.85	0.20	13.6	-0.03	-0.14	0.0
320	5.41	1.16	5.5	0.98	0.28	0.3
326	6.40	0.39	6.0	1.22	0.17	2.0
330	1.57	1.07	6.9	0.08	0.02	1.8
334	5.27	0.30	5.3	1.20	0.30	-4.8
337	19.50	0.25	1.7	0.52	0.13	1.9
345	8.21	0.23	1.6	0.42	0.07	0.0
347	7.33	0.41	2.1	0.81	0.34	0.0
352	8.00		1.5		0.06	1.9
362	2.73	0.15	11.7	0.38	-0.05	0.0
365	4.08	1.11	2.9	0.40	0.13	

Table 3. (continued)

JW	P(days)	Mass($M_\odot$)	R_{proj}($'$)	E(I-K)	E(H-K)	EW(CaII)
378	9.03	0.31	1.1	1.08		1.5
379	11.30	0.13	7.0	0.07	-0.08	
381	16.20	0.32	7.2	1.26	0.34	0.0
388	9.08	0.38	8.0	0.06	0.06	1.2
406	2.25	0.21	6.2	0.31	0.06	1.7
417	7.41	0.35	1.3	0.56	0.60	0.0
437	2.34	0.31	1.2	0.53	0.29	1.4
439	8.30	0.28	6.0	0.62	0.08	0.7
454	8.67	0.81	0.8	0.39	0.27	-1.0
466	6.17	0.21	13.3	0.35	-0.01	
470	10.70	0.83	1.2		0.69	6.1
478	5.74	0.20	1.9	0.43	0.12	
479	8.71	2.62	0.5	0.57	0.31	2.0
481	6.56	0.23	1.7	0.35	0.18	0.0
485	9.66	0.33	3.1	1.18	0.44	0.8
498	7.42	0.37	9.6		0.47	
526	1.68	0.47	0.7	0.74		1.2
536	9.23	1.79	0.8	0.66	0.36	1.7
544	3.42	1.19	1.9	-0.17	0.12	1.6
553	8.35	0.95	0.5	0.17		-0.7
559	2.27	0.16	1.5	-0.31	0.19	-5.1
563	5.80	0.36	7.7	-0.35		
567	8.53	1.04	0.7	-0.17	0.07	-1.7
576	2.01	0.26	6.2	0.23	0.00	0.0
589	14.30	2.79	0.9	0.11	0.02	-0.6
601	2.22	1.17	7.2	0.05	0.03	2.5
636	5.59	0.29	2.4	0.79	0.43	
639	5.24	0.22	10.6		-0.11	
641	3.17	2.24	3.4	0.12	0.06	0.0
648	34.50	0.27	1.0			0.9
660	6.15	6.41	2.0	0.72	0.14	
664	7.20	0.51	6.8	-0.18	0.02	1.4
669	1.81	2.13	1.2	0.14	0.02	1.8
673	1.44	0.75	8.1	0.81	0.38	1.3
678	13.00	1.38	2.0	0.24	0.02	
681	10.50	0.44	1.3	1.74		
683	11.50	0.47	3.6	0.28	0.08	1.9
691	6.34	0.16	8.5	0.22	0.02	0.0
695	11.50	0.27	3.6	2.29	0.21	0.6
704	6.87	0.40	5.1			
710	7.59	0.27	1.7	0.68	0.77	-2.1
716	3.95	0.15	4.3	1.15	0.44	-2.7
717	4.00	0.23	8.4		0.34	0.0
721	2.45	0.34	1.5	0.82	0.24	-3.8
727	6.03	0.28	8.4	0.75	0.23	0.8
731	7.64	0.35	12.6	0.28	0.04	2.2
735	5.21	0.21	5.1	0.75		0.0
758	2.51	0.15	3.7	0.48	0.24	-2.0

Table 3. (continued)

JW	P(days)	Mass($M_\odot$)	R_{proj}($'$)	E(I-K)	E(H-K)	EW(CaII)
765	2.42	0.19	14.1	0.09	-0.02	1.3
786	8.81	0.35	4.0	1.30	0.45	0.0
787	9.00	0.30	7.3			0.6
788	4.82	0.17	7.6	0.28	0.16	0.0
790	2.74	2.04	14.9	0.12	0.06	2.2
792	10.30	0.30	3.4	1.05	0.26	1.4
794	2.62	1.93	8.6	0.03	0.01	
795	1.55	2.51	4.9	0.12	0.06	1.7
811	11.10	0.29	6.8	1.25		0.0
813	2.85	0.31	4.1	0.56	0.07	1.9
815	6.42	0.22	4.9	0.52	0.16	0.0
817	2.23	0.15	5.8	0.22		
819	5.76	0.14	7.0	0.12	-0.02	1.3
823	9.00	0.15	5.4	0.25	0.06	0.0
826	9.57	0.73	3.3	3.01		-6.3
830	9.23	0.25	3.4	0.63	0.19	1.8
835	8.85	0.23	12.1	0.24	-0.02	0.0
836	12.20	0.35	6.6	1.10	0.25	0.9
837	10.60	0.34	7.6	0.62	0.06	1.2
839	7.52	0.15	3.6	-1.41	-0.17	1.2
843	5.38	0.27	8.5	0.02	-0.14	0.0
850	7.78	0.40	4.2	0.73	0.32	-4.1
855	7.08	0.30	6.2	0.79	0.16	0.0
860	6.33	0.20	5.3	0.15	-0.02	2.1
863	7.91	0.21	8.1	0.71	0.11	0.0
866	6.76	1.95	8.6	0.18	0.03	
872	4.19	0.13	6.2	0.60	0.07	0.4
878	5.54	0.14	7.7	-0.06	-0.11	0.0
880	3.51	0.18	7.3	-0.10	-0.10	0.0
890	1.10	0.27	4.9	0.46	0.04	1.6
892	8.56	0.65	8.4			1.0
907	1.65	1.14	7.4	-0.20	-0.06	1.8
914	7.71	0.28	9.0	0.71	0.32	0.0
930	2.88	0.57	6.6	-0.71	-0.01	5.2
933	5.98	0.17	7.3	0.05	0.00	1.0
972	8.07	0.33	11.5	0.38	-0.02	1.2
984	8.44	0.22	8.8	0.45	0.01	0.7
H3128	2.47		6.8			

Table 4. Spearman Coefficients and Least Squares Slopes

Correlation	Coefficient	Significance	Slope	Error
Projected Radius vs. Rotation Period	-0.24	0.005	-0.188	0.019
H-K excess vs. Rotation Period	0.40	0.0007	0.015	0.031
I-K excess vs. Rotation Period	0.39	0.0007	0.066	0.030
E.W. (CaII) vs. Rotation Period	-0.32	0.010	-0.062	0.024